

The earliest galaxies seen in 21 cm line absorption

Yidong Xu^{1,2,4*}, Andrea Ferrara³, and Xuelei Chen^{4,5}

¹*Department of Astronomy, School of Physics, Peking University, Beijing 100871, China*

²*SISSA/International School for Advanced Studies, Via Beirut 4, 34014 Trieste, Italy*

³*Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy*

⁴*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*

⁵*Center for High Energy Physics, Peking University, Beijing 100871, China*

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ABSTRACT

We investigate the 21 cm absorption lines produced by non-linear structures during the early stage of reionization, i.e. the starless minihalos and the dwarf galaxies. After a detailed modelling of their properties, with particular attention to the coupling physics, we determine their 21 cm absorption line profiles. The infalling gas velocity around minihalos/dwarf galaxies strongly affects the line shape, and with the low spin temperatures outside the virial radii of the systems, gives rise to horn-like line profiles. The optical depth of a dwarf galaxy is reduced for lines of sight penetrating through its HII region, and especially, a large HII region created by a dwarf galaxy with higher stellar mass and/or a top-heavy initial mass function results in an optical depth trough rather than an absorption line. We compute synthetic spectra of 21 cm forest for both high redshift quasars and radio afterglows of gamma ray bursts (GRBs). Even with the planned SKA, radio afterglows of most if not all GRBs would still be too dim to be the background sources for high resolution (1 kHz) observations, but absorption lines can be easily detected towards a high- z quasar. Broadband observation against GRB afterglows can also be used to reveal the evolving 21 cm signal from both minihalos and dwarf galaxies if there was no X-ray background or it was extremely weak, but it becomes difficult if an early X-ray background existed. Hence the 21 cm absorption could be a powerful probe of the presence/intensity of the X-ray background and the thermal history of the early universe.

Key words: line: profiles – galaxies: dwarf – galaxies: high-redshift – cosmology: theory.

1 INTRODUCTION

The formation of the earliest galaxies and the cosmic reionization are among the milestones in the history of the universe. As the first stars form in the earliest non-linear structures, they illuminate the ambient intergalactic medium (IGM) and start the reionization process of hydrogen. Based on an instantaneous reionization model, the polarization data of cosmic microwave background (CMB) constrain the redshift of reionization to be $z_{\text{reion}} \approx 10.5$ (Larson et al. 2010), while the Gunn-Peterson troughs (Gunn & Peterson 1965) shown in quasar (QSO) absorption spectra suggest that the reionization of hydrogen was very nearly complete by $z \approx 6$ (e.g. Fan et al. 2006). However, at present we are still unable to observe the earliest galaxies directly, and our current understanding on the reionization process is only based on theoretical models (e.g. Furlanetto et al. 2004) and simulations (e.g. Trac et al. 2008).

The most promising probe of the cosmic reionization is the redshifted 21 cm transition of HI which is directly related to the neutral component of the IGM (see e.g. Furlanetto, Oh & Briggs 2006 for a review). Unlike the Ly α resonance line, the 21 cm

line could hardly be saturated because of its extremely small Einstein coefficient ($A_{10} = 2.85 \times 10^{-15} \text{ s}^{-1}$), so it traces well the reionization history, especially during the early stages. Using the CMB as the background radio source, 21 cm tomography could map out the three dimensional structure of the emission or absorption of 21 cm photons by the IGM (e.g. Madau et al. 1997; Tozzi et al. 2000). However, it requires the deviation of the spin temperature from the CMB temperature and may not be feasible for certain epochs; it could not resolve structures smaller than ~ 1 Mpc; and it has a number of observational challenges (Furlanetto, Oh & Briggs 2006). Complementary to the 21 cm tomography, the 21 cm forest observation detects absorption lines of intervening structures against high redshift radio sources (Carilli et al. 2002; Furlanetto & Loeb 2002; Furlanetto 2006), and it is immune to most of the above difficulties encountered by the tomography observation. As it is very sensitive to gas temperature (Xu et al. 2009), it provides a useful tool to constrain the X-ray heating in the early universe. And also, the 21 cm forest is a promising probe that could possibly detect high redshift minihalos, which are important for determining the mean clumping factor of the IGM and putting limits on small scale structure formation. Here we focus on the absorption experiments and investigate the 21 cm

* E-mail: xuyd@vega.bac.pku.edu.cn

absorption lines produced by the non-linear structures during the epoch of reionization.

The forest observation relies on the availability of luminous radio sources beyond the epoch of reionization. One possibility is the high redshift quasars which have been observed up to $z = 6.43$ (Willott et al. 2007), and a radio-loud quasar at $z = 6.12$ was discovered by McGreer et al. (2006). Using high- z quasars or radio galaxies as backgrounds, Carilli et al. (2002) and Xu et al. (2009) have examined the possibility of detecting 21 cm absorption by the neutral IGM based on simulations. Another possible option is the radio afterglows of high- z gamma ray bursts (GRBs). It is believed that some of the long duration bursts are produced by the explosions of massive stars. The first stars are thought to be likely very massive, and may produce bright GRBs which would be detectable up to a redshift as high as 60 (Naoz & Bromberg 2007). Recently, GRB 090423 was discovered at $z = 8.1$ (Salvaterra et al. 2009, while Tanvir et al. 2009 reported its redshift to be $z = 8.26$), establishing the new redshift record of observation for all objects except for the CMB. The radio afterglow of a GRB can be observed out to a very late time when the outflow becomes sub-relativistic (e.g. Pihlström et al. 2007), and considering the cosmic time dilation, it offers us an adequate integration time. One possible problem with the GRB radio afterglow is that at very low frequency, synchrotron self-absorption may become important which may reduce the radio flux. Nonetheless, some GRB radio afterglows may be sufficiently bright at the relevant frequency ranges.

In order to plan such observations, we need to know what kind of signals will be produced by the early structures, and to understand the physics behind the expected signals. In this paper, we provide a detailed modeling of the 21 cm absorption lines produced by minihalos and dwarf galaxies during the epoch of reionization, and explore the physical origins of the line profiles. We generate synthetic spectra of both quasars and GRB afterglows, on top of which the 21 cm absorption lines are superposed. Projecting the capability of future instruments, we discuss the prospects of detecting the 21 cm signals from these non-linear objects in the early universe.

This paper is arranged as follows. In Section 2, we describe the physical model involved with the 21 cm absorptions, including the halo model for high redshifts, the star burst criterion, a possible X-ray background, the physical processes taking place in minihalos and dwarf galaxies respectively, and the Ly α background produced by these early galaxies. In Section 3, we show the spin temperatures and 21 cm line profiles of minihalos and dwarf galaxies for various parameters. Statistical results including line number density, theoretical spectrum, and the equivalent width (EW) distribution are given in Section 4. Then, in Section 5 we study the feasibility of the 21 cm observation by making mock spectra of both quasar and radio afterglow of GRB. Finally, we summarize and discuss our results in Section 6.

Throughout this paper, we adopt the cosmological parameters from WMAP5 measurements combined with SN and BAO data: $\Omega_b = 0.0462$, $\Omega_c = 0.233$, $\Omega_\Lambda = 0.721$, $H_0 = 70.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\sigma_8 = 0.817$, and $n_s = 0.96$ (Komatsu et al. 2009).

2 THE MODEL

We start with a description of various aspects of physics involved with determining the absorption spectrum of 21 cm lines. This includes the high redshift number density of dark matter halos, gas distribution inside and around halos, the criterion of star forma-

tion, the X-ray and Ly α background, and a detailed modeling of the physical properties of starless minihalos and galaxies, respectively. Among these properties, the ionization state, the gas temperature distribution, and the Ly α photon density are especially important for determining the strength and line profiles of the 21 cm absorption by minihalos/dwarf galaxies.

2.1 The Halo Model

In order to model the halo number density at high redshift, we use the Sheth-Tormen halo mass function, which is based on an ellipsoidal model for perturbation collapse and fits well the simulation results. The comoving number density of halos at redshift z with mass in the interval $(M, M + dM)$, can be written as (Sheth & Tormen 1999)

$$n(M, z) dM = F_{\text{ST}}(\sigma, z) \frac{\bar{\rho}_0}{M} \frac{d \ln \sigma^{-1}}{dM} dM, \quad (1)$$

where

$$F_{\text{ST}}(\sigma, z) = A \sqrt{\frac{2a}{\pi}} \left[1 + \left(\frac{\sigma^2}{a \delta_{sc}^2} \right)^p \right] \frac{\delta_{sc}}{\sigma} \exp \left[-\frac{a \delta_{sc}^2}{2 \sigma^2} \right]. \quad (2)$$

Here $\bar{\rho}_0$ is the cosmic mean density of the total matter today, $\sigma = \sigma(M)$ is the r.m.s. of a Gaussian density field smoothed on a mass scale M with a spherical top-hat filter of radius R , where R is equivalent to M in a fixed cosmology as $R = (3M/4\pi\bar{\rho}_0)^{1/3}$, and $\delta_{sc} = 1.686/D(z)$ is the critical overdensity required for spherical collapse at redshift z , extrapolated to the present time using the linear theory, where $D(z)$ is the linear growth factor. The correction factors $a = 0.707$, $p = 0.3$, and $A = 0.3222$ were introduced as appropriate for ellipsoidal collapse (Sheth & Tormen 2002; Sheth, Mo & Tormen 2001).

The 21 cm signal depends on the gas content of minihalos or galaxies, and the gas fraction in halos will be suppressed by the heating processes during the reionization. Therefore, we set the lower limit of the halo mass to be the characteristic mass M_C at which halos on average could only retain half of their baryons. The characteristic mass depends on the halo merger history and the thermal evolution of the universe (Gnedin 2000; Okamoto et al. 2008). At high redshift that we are considering ($z > 6$), however, the filtering mass M_F provides a good fit to the characteristic mass M_C (Okamoto et al. 2008). Including the global heating process by an X-ray background (see section 2.3 in the following), we compute the thermal evolution of the universe and find that this mass scale is $\sim 10^6 M_\odot$ beyond redshift 7 for an early X-ray background not higher than 20% of the intensity today. For high redshifts of interest, it is not very sensitive to the uncertain intensity of the X-ray background because of the delayed response of the gas density distribution to the change in the gas temperature. However, if the early X-ray background was as high as today, or even higher, it would have moderate effect in raising the Jeans mass and the filtering mass (see the right panel of Fig.2). So we take the halo mass range of $[10^6 M_\odot, 10^{10} M_\odot]$ for an X-ray background not higher than 20% of today's value, but also consider its effect on the minimum halo mass for higher intensities of the X-ray background (see section 4). The range covers the characteristic halo mass and most of the galaxies that are responsible for the reionization (Choudhury & Ferrara 2007).

In the following, we use the NFW density profile for dark matter distribution inside of the virial radius r_{vir} of a halo (Navarro, Frenk & White 1997). In general, the key parameter in the NFW profile, the concentration parameter c , depends on the

halo mass as well as its redshift. Unfortunately, the concentration parameter found from low redshift simulations (Cooray & Sheth 2002) is not directly applicable to the epoch of reionization. Thanks to the resimulation technique, Gao et al. (2005) have simulated an example of the first halos from very high redshift with extremely high resolution, and its density profile is derived in each resimulation at the final time. Here we make use of their results. Assuming that c is inversely proportional to $(1+z)$, as indicated by low redshift results, we make a 4th-order polynomial fit to the simulated points in the logarithmic space of halo mass.

For the distribution of gas within the dark matter halo, we assume that the gas is in hydrostatic equilibrium with the dark matter, and have a spherical distribution. We expect gas in the high- z (and in general low-mass) galaxies have a rounder distribution rather than settling into a disc because: (a) their circular velocities are comparable to the sound speed, making the gas more rounded than flat; (b) at such high redshifts, there may not be enough time for the gas to settle in a smooth disk. With the NFW profile of dark matter distribution, one can derive the gas density distribution analytically (Makino et al. 1998):

$$\ln \rho_g(r) = \ln \rho_{g0} - \frac{\mu m_p}{2 k_B T_{\text{vir}}} [v_e^2(0) - v_e^2(r)], \quad (3)$$

where ρ_{g0} is the central gas density, μ is the mean molecular weight of the gas depending on the ionization state, m_p is the proton mass, k_B is the Boltzmann constant, and T_{vir} is the virial temperature of the halo. Here $v_e(r)$ denotes the gas escape velocity at radius r , which can be written as

$$v_e^2(r) = 2 \int_r^\infty \frac{GM(r')}{r'^2} dr' = 2 V_c^2 \frac{F(cx) + \frac{cx}{1+cx}}{x F(c)}, \quad (4)$$

where $V_c^2 \equiv GM/r_{\text{vir}}$ is the circular velocity at the virial radius, $x \equiv r/r_{\text{vir}}$, c is the halo concentration, and $F(c) = \ln(1+c) - c/(1+c)$. The maximum escape velocity is reached at the center of the halo, $v_e^2(0) = 2 V_c^2 c/F(c)$. In Eq.(3), the central density ρ_{g0} is determined by the condition that the total baryonic mass fraction within the virial radius is equal to Ω_b/Ω_m , which gives

$$\frac{\rho_{g0}}{\bar{\rho}_m} = \frac{(\Delta_c/3) c^3 (\Omega_b/\Omega_m) e^A}{\int_0^c (1+t)^{A/t} t^2 dt}, \quad (5)$$

where $\bar{\rho}_m = \bar{\rho}_m(z)$ is the mean matter density of the universe at redshift z , $A \equiv 2c/F(c)$, and Δ_c is the mean density of a virialized halo with respect to the cosmic mean value $\bar{\rho}_m$ (Bryan & Norman 1998): $\Delta_c = 18\pi^2 + 82(\Omega_m^z - 1) - 39(\Omega_m^z - 1)^2$, where $\Omega_m^z = \Omega_m(1+z)^3/[\Omega_m(1+z)^3 + \Omega_\Lambda]$.

To determine the gas distribution outside r_{vir} , one has to keep in mind that the gas slowly falls into the halo because of the gravitational force of the halo, so the gas has a peculiar (i.e. infalling) velocity which could be important for the 21 cm line. Also, due to the large cross-section at large radii, there is a high probability for the line of sight to go through these external parts of the halos, and this infalling gas has to be included in the calculation. Barkana (2004) has derived a model for the expected profiles of infalling matter around virialized halos based on the extended Press-Schechter (EPS) formalism (Bond et al. 1991). This ‘‘Infall Model’’¹ can also be used to compute the final peculiar velocity profiles around virialized halos as well. The total velocity of the gas is the sum of the peculiar velocity and the Hubble expansion. In these infalling

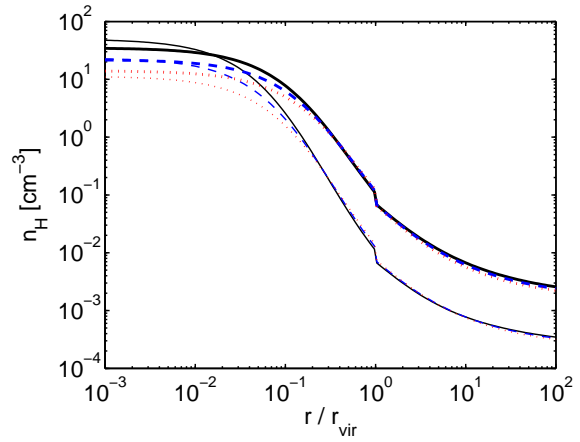


Figure 1. The hydrogen number density profiles in and around dark matter halos of different masses: $M = 10^6 M_\odot$ (solid curves), $M = 10^7 M_\odot$ (dashed curves), and $M = 10^8 M_\odot$ (dotted curves), respectively. The thick curves are for redshift 20, while the thin curves are for redshift 10.

regions around halos, we assume that the gas overdensity and velocity field follow the dark matter perfectly, with the scaling factor Ω_b/Ω_m .

Several illustrative curves of the total hydrogen number density profiles are shown in Fig.1 for various halo masses and two sets of redshifts. A constant hydrogen fraction of primordial value $X_H = 0.752$ is assumed here (Spergel et al. 2007). The halos with smaller mass and lower redshift are more concentrated. We can see that there are discontinuities at r_{vir} . That is because when we adopt the gas density profile above, we are also assuming that the virialization shock is located right at the virial radius, and at the shock radius density and temperature jumps are expected. The exact position of the shock radius is subject to debate, and may depend on the assembly history of the halo. For an cosmology with $\Omega_m = 1$, Bertschinger (1985) found that the accretion shock forms at the radius $R_{90.8}$ which encloses a mean dark matter density of 90.8 times the cosmic mean, while Abel et al. (2002) suggests that the shock radius is close to the virial radius. Below we assume that the shock is located at the virial radius, but note that the exact position of the shock radius has only a small effect on the resulting 21 cm signal (see the next section).

2.2 Star Formation Criterion

After the formation of dark matter halos, some of the halos could form stars inside while others could not, depending mainly on the cooling processes in each halo (see McKee & Tan 2008 for a recent review). As for those halos with star formation, a star burst is more likely than continuous formation at this early epoch, because, small objects are very sensitive to feedbacks and therefore, as soon as the first stars formed in the galaxy, their radiation and induced supernovae could heat and eject the surrounding gas, quenching subsequent star formation. In order to determine whether a halo is able to undergo a star burst, here we use a timescale criterion for star formation. If the time required for a halo to start forming stars is longer than the Hubble time at the halo redshift, it will remain starless, i.e. a system that is usually identified as a *minihalo*. Otherwise, the halo has enough time to cool and collapse to form stars, and becomes a *dwarf galaxy*. The timescale required for turning on a star burst is modeled as the maximum between the free-fall time

¹ Public code for this ‘‘Infall Model’’ is available at <http://wise-obs.tau.ac.il/~barkana/codes.html>.

t_{ff} and the cooling time t_{cool} , i.e. $t_{\text{SB}} = \max\{t_{\text{ff}}, t_{\text{cool}}\}$, where $t_{\text{ff}} = (3\pi/32 G\rho)^{1/2}$. As for the minihalos and dwarf galaxies in the early universe, the main coolant is the molecular hydrogen (Abel et al. 2002; Bromm et al. 2002; Bromm & Larson 2004), and t_{cool} is the H_2 cooling timescale. Defining $t_{\text{cool}} \equiv T/\dot{T}$, one can obtain (Tegmark et al. 1997)

$$t_{\text{cool}} \approx 48,200 \text{ yr} \left(1 + \frac{10 T_3^{7/2}}{60 + T_3^4}\right)^{-1} e^{512K/T} (fn_1)^{-1}, \quad (6)$$

where $T_3 \equiv T/10^3 \text{ K}$, $n_1 \equiv n_{\text{H}}/1 \text{ cm}^{-3}$, and the f is the fraction of hydrogen in molecular form. This fraction varies with time and to get the precise value at virialization it would be necessary to follow the entire collapse history, but after the virialization the H_2 fraction of a halo always saturates at $\sim 10^{-3}$ (Tegmark et al. 1997). For simplicity, we use $f = 10^{-3}$ hereafter.

The cooling and collapse processes start from the halo formation time, which is usually defined as the time at which a halo first acquires half of its final mass. There are several predictors for the formation redshift distribution of dark matter halos, such as the standard EPS model (Lacey & Cole 1993), the ellipsoidal collapse model (Sheth & Tormen 2002), and the non-spherical collapse boundary model (Chiueh & Lee 2001). At high redshift, the EPS model fits the simulation results best (Lin et al. 2003). According to the EPS model (Lacey & Cole 1993), the cumulative probability that a halo with mass M_2 at redshift z_2 has a formation time t_{F} prior to t_1 or a formation redshift z_{F} higher than z_1 is

$$P(t_{\text{F}} < t_1 | M_2, t_2) \equiv P(z_{\text{F}} > z_1 | M_2, z_2) \\ = \int_{S_2}^{S_h} \frac{M_2}{M_1} f_{S_1}(S_1, \delta_{sc1} | S_2, \delta_{sc2}) dS_1, \quad (7)$$

where $f_{S_1}(S_1, \delta_{sc1} | S_2, \delta_{sc2}) dS_1$ is the conditional probability function:

$$f_{S_1}(S_1, \delta_{sc1} | S_2, \delta_{sc2}) dS_1 = \frac{\delta_{sc1} - \delta_{sc2}}{\sqrt{2\pi}(S_1 - S_2)^{3/2}} \\ \times \exp\left[-\frac{(\delta_{sc1} - \delta_{sc2})^2}{2(S_1 - S_2)}\right] dS_1 \quad (S_1 > S_2, \delta_{sc1} > \delta_{sc2}). \quad (8)$$

Here S is defined as the variance of density field smoothed on a mass scale M , $S_1 \equiv \sigma^2(M_1)$, $S_2 \equiv \sigma^2(M_2)$, $S_h \equiv \sigma^2(M_2/2)$, $\delta_{sc1} \equiv \delta_{sc}(z_1)$, and $\delta_{sc2} \equiv \delta_{sc}(z_2)$. Given any halo mass at the redshift of interest, we differentiate Eq.(7) with respect to z_{F} to get the differential distribution of the halo formation redshift, then its formation redshift z_{F} is chosen by Monte-Carlo sampling of the distribution curve.

The star burst time is simply $t_{\text{s}} = t_{\text{F}} + t_{\text{SB}}$. When the criterion $t_{\text{s}} < t_{\text{H}}$ is satisfied, a star burst occurs at time t_{s} , while $t_{\text{s}} > t_{\text{H}}$ implies that the halo is not able to form stars within a Hubble time.

2.3 The 21 cm Optical Depth

With a high redshift GRB afterglow as the background source, the neutral hydrogen in the IGM absorbs the 21 cm photons along the line of sight. For the diffuse IGM beyond those regions affected by the gravity of non-linear structures, it expands uniformly with the Hubble flow, then the optical depth is (Field 1959; Madau et al. 1997; Furlanetto, Oh & Briggs 2006)

$$\tau_{\text{IGM}} = \frac{3 h_{\text{P}} c^3 A_{10}}{32 \pi k_{\text{B}} \nu_{10}^2} \frac{n_{\text{HI}}(z)}{T_{\text{S}} H(z)}, \quad (9)$$

where h_{P} is the Planck constant, c is the speed of light, $A_{10} = 2.85 \times 10^{-15} \text{ s}^{-1}$ is the Einstein coefficient for the spontaneous

decay of the 21 cm transition, and $\nu_{10} = 1420.4 \text{ MHz}$ is the rest frame frequency of the 21 cm transition. Here n_{HI} , T_{S} , and H are the neutral hydrogen number density, spin temperature, and the Hubble parameter, respectively.

In order to compute the n_{HI} and T_{S} , a global description of the ionization and thermal evolution of the IGM is required. Several authors (e.g. Oh & Haiman 2003; Furlanetto 2006) have shown that X-rays will likely heat the IGM significantly before reionization completes. Also, if it existed, it could partially ionize the IGM, suppress the formation of low mass minihalos, and heat the infall regions around surviving minihalos and dwarf galaxies. However, the heating processes are quite uncertain during the early stages of reionization, and it is unknown what the X-ray intensity should be at high redshifts. Here we include only the X-ray background heating which is the most important heating mechanism (Furlanetto 2006). Calibrating the X-ray ($> 0.2 \text{ keV}$) luminosity of high- z objects to nearby starburst galaxies, we have (Gilfanov et al. 2004; Furlanetto 2006)

$$L_{\text{X}} = 3.4 \times 10^{40} f_{\text{X}} \left(\frac{\text{SFR}}{1 M_{\odot} \text{ yr}^{-1}} \right) \text{ erg s}^{-1}, \quad (10)$$

where SFR is the star formation rate, and f_{X} is a correction factor accounting for the unknown properties of X-ray emitting sources in the early universe. We will set $f_{\text{X}} = 0.1$ as the fiducial value as the early galaxies are probably much less productive of X-rays than the nearby starburst galaxies, but we take f_{X} as a free parameter and vary the level of X-ray background by choosing different values of f_{X} to illustrate the sensitivity of our results to this uncertain process. Assuming that the star formation rate is proportional to the rate at which matter collapses into galaxies (Furlanetto 2006), the total X-ray emissivity ϵ_{X} can be written as:

$$\frac{2}{3} \frac{\epsilon_{\text{X}}}{k_{\text{B}} n H(z)} = 5 \times 10^4 \text{ K} f_{\text{X}} \left(\frac{f_{\star}}{0.1} \frac{df_{\text{coll}}/dz}{0.01} \frac{1+z}{10} \right), \quad (11)$$

where n is the total particle number density (including hydrogen atoms, protons, electrons, and helium), f_{coll} is the fraction of matter in collapsed halos with $M > M_{\text{min}}$, where M_{min} is typically taken to be the mass threshold for atomic cooling which has a virial temperature $T_{\text{vir}} = 10^4 \text{ K}$, and f_{\star} is the star formation efficiency normalized to the cosmic baryon content. We use a mass-dependent f_{\star} provided by the handy fit in Salvadori & Ferrara (2009), and evaluate it at M_{min} for the most populous galaxies for approximation.

A fraction of energy in the X-ray background contributes to the heating of the IGM, and another fraction contributes to the ionization of IGM, these fractions depend on the ionizing state of the IGM (Valdés & Ferrara 2008). In the absence of an ionizing UV background, the ionization would be caused mainly by these X-ray photons, and we take into account both the primary and the secondary ionization processes in computing this $\bar{x}_i(z)$, assuming ionization equilibrium. Then the evolution of the gas temperature in the IGM can be described by (Furlanetto 2006)

$$\frac{dT_{\text{K}}}{dt} = -2 H(z) T_{\text{K}} + \frac{2}{3} \frac{\epsilon_{\text{comp}}}{k_{\text{B}} n} + \frac{2}{3} \frac{\epsilon_{\text{X,h}}}{k_{\text{B}} n}, \quad (12)$$

where the first item on the right-hand side describes the adiabatic cooling due to Hubble expansion, ϵ_{comp} is the Compton heating/cooling rate per unit (physical) volume, and $\epsilon_{\text{X,h}}$ denotes the part of the total X-ray background going into heating. The Compton term is (see e.g. Furlanetto 2006)

$$\frac{2}{3} \frac{\epsilon_{\text{comp}}}{k_{\text{B}} n} = \frac{\bar{x}_i}{1 + f_{\text{He}} + \bar{x}_i} \frac{8 \sigma_{\text{T}} u_{\gamma}}{3 m_e c} (T_{\gamma} - T_{\text{K}}). \quad (13)$$

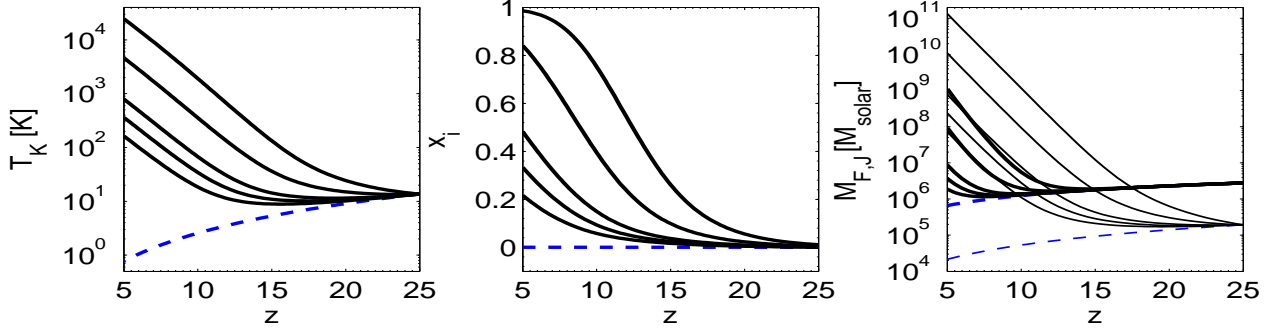


Figure 2. The evolution of the global temperature (*left panel*), the mean ionized fraction (*central panel*), and the filtering mass and Jeans mass (*right panel*) of the IGM. The dashed curves are for $f_X = 0$, and the solid curves from bottom to top in each panel are for $f_X = 0.05$, $f_X = 0.1$, $f_X = 0.2$, $f_X = 1.0$, and $f_X = 5.0$, respectively. In the right panel, the thin and thick curves illustrate the evolutions of the Jeans mass and the filtering mass respectively.

Here f_{He} is the He fraction by number, $\sigma_T = 6.65 \times 10^{-25} \text{cm}^2$ is the Thomson scattering cross section, $u_\gamma = (4\sigma/c) T_\gamma^4 \propto (1+z)^4$ is the energy density of the CMB photons, where $\sigma = 5.67 \times 10^{-5} \text{erg cm}^{-2} \text{s}^{-1} \text{K}^{-4}$ is the Stefan-Boltzmann constant, and m_e is the electron mass. The evolutions of the IGM temperature and the mean ionized fraction caused by X-rays are shown in the left and central panels of Fig.2 for several values of f_X . The case of $f_X = 0$ is denoted by the dashed curves. It corresponds to the situation in which there is no X-ray background, and the IGM temperature decreases adiabatically with a mean ionized fraction of 3×10^{-4} which is the residual electron fraction left over after the recombination. The solid curves from bottom to top in each panel take $f_X = 0.05$, $f_X = 0.1$, $f_X = 0.2$, $f_X = 1$, and $f_X = 5$, respectively. Here we also illustrate the corresponding evolutions of the Jeans mass (thin curves) and the filtering mass (thick curves) in the right panel of Fig.2. The filtering mass, which provides a reasonable fit to the characteristic mass, is $M_F \sim 10^6 M_\odot$ for $f_X \lesssim 0.2$, $M_F \sim 2 \times 10^6 M_\odot$ for $f_X \sim 1$, and $M_F \sim 5 \times 10^6 M_\odot$ for $f_X \sim 5$ at $z \sim 10$.

The IGM creates a global decrement in the afterglow spectrum, on top of which minihalos and dwarf galaxies produce deep and narrow absorption lines. The main broadening mechanism of each absorption line is the thermal broadening with the Doppler profile. The 21 cm optical depth of an isolated object is the integral of the absorption coefficient along the line of sight (Field 1959; Madau et al. 1997; Furlanetto & Loeb 2002):

$$\tau(\nu) = \frac{3 h_P c^3 A_{10}}{32 \pi^{3/2} k_B} \frac{1}{\nu^2} \times \int_{-\infty}^{+\infty} \frac{n_{\text{HI}}(r)}{b(r) T_S(r)} \exp \left[-\frac{(u(\nu) - \bar{v}(r))^2}{b^2(r)} \right] dx, \quad (14)$$

where $b(r)$ is the Doppler parameter of the gas, $b(r) = \sqrt{2 k_B T_K(r) / m_H}$, $u(\nu) \equiv c(\nu - \nu_{10}) / \nu_{10}$, and $\bar{v}(r)$ is bulk velocity of gas projected to the line of sight at the radius r . Inside of the virial radius, the gas is thermalized, and $\bar{v}(r) = 0$, while the gas outside the virial radius has a bulk velocity contributed from both the infall and the Hubble flow according to the ‘‘Infall Model’’. The coordinate x is related to the radius r by $r^2 = (\alpha r_{\text{vir}})^2 + x^2$, where

α is the impact parameter of the penetrating line of sight in units of r_{vir} .

The spin temperature of neutral hydrogen is defined by the relative occupation numbers of the two hyperfine structure levels, and it is determined by three competing processes: (1) absorption of CMB photons; (2) collisions with other hydrogen atoms, free electrons, and other species; and (3) scattering with UV photons. The equilibrium spin temperature is given by (Field 1958; Furlanetto, Oh & Briggs 2006):

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_C^{-1}}{1 + x_c + x_\alpha}, \quad (15)$$

where $T_\gamma = 2.726(1+z)$ K is the CMB temperature at redshift z , T_K is the gas kinetic temperature, and T_C is the effective color temperature of the UV radiation. In most cases, $T_C = T_K$ due to the frequent $\text{Ly}\alpha$ scattering (Furlanetto, Oh & Briggs 2006). The collisional coupling is described by the coefficient x_c , and x_α is the coupling coefficient of the $\text{Ly}\alpha$ pumping effect known as the Wouthuysen-Field coupling (Wouthuysen 1952; Field 1958). The main contributions to x_c are H-H collisions and H- e^- collisions, and it can be written as

$$x_c = x_c^{\text{eH}} + x_c^{\text{HH}} = \frac{n_e \kappa_{10}^{\text{eH}}}{A_{10}} \frac{T_\star}{T_\gamma} + \frac{n_{\text{HI}} \kappa_{10}^{\text{HH}}}{A_{10}} \frac{T_\star}{T_\gamma}, \quad (16)$$

where $T_\star = 0.0682$ K is the equivalent temperature of the energy splitting of the 21 cm transition, and κ_{10}^{eH} and κ_{10}^{HH} are the de-excitation rate coefficients in collisions with free electrons and hydrogen atoms respectively. These two coefficients at different temperatures are tabulated in Furlanetto, Oh & Briggs (2006). The coupling coefficient x_α is proportional to the total scattering rate between $\text{Ly}\alpha$ photons and hydrogen atoms,

$$x_\alpha = \frac{4 P_\alpha}{27 A_{10}} \frac{T_\star}{T_\gamma}, \quad (17)$$

where the scattering rate P_α is given by

$$P_\alpha = c \sigma_\alpha \frac{n_\alpha^{\text{tot}}}{\Delta \nu_D} = 4\pi \sigma_\alpha J_\alpha. \quad (18)$$

Here $\sigma_\alpha \equiv \frac{\pi e^2}{m_e c} f_\alpha$ where $f_\alpha = 0.4162$ is the oscillator strength

of the Ly α transition, n_{α}^{tot} is the total number density of Ly α photons, J_{α} is the number intensity of the Ly α photons, and $\Delta\nu_D = (b/c) \nu_{\alpha}$ is the Doppler width with b being the Doppler parameter and ν_{α} being the Ly α frequency.

In addition to the global $\bar{x}_i(z)$ and $T_{\text{IGM}}(z)$, to compute the line profiles of the 21 cm absorptions by minihalos and dwarf galaxies, we need a detailed prescription of the ionization state, the temperature profile, and the Ly α photon density in and around these objects. We model respectively these properties of both minihalos and dwarf galaxies, as well as the intensity of Ly α background in the following.

2.3.1 Modeling the minihalos

Minihalos refer to those small halos that are not capable of hosting stars, and they represent a very numerous population according to the halo mass function. As we are considering the early stages of reionization, when the IGM was slightly ionized with some rare sites illuminated by the earliest galaxies, the background radiation field has not been set up. However, the gas in minihalos, which has much higher density, could be collisionally ionized partially, depending on its temperature. The HI fraction is computed from collisional ionization equilibrium (CIE)

$$n_e n_{\text{HI}} \gamma = \alpha_B n_e n_p, \quad (19)$$

where γ is the collisional ionization coefficient (Cen 1992), and α_B is the case B recombination coefficient (Hui & Gnedin 1997) which is appropriate for the high- z and low-mass halos as well as the IGM that are far from fully ionized.

The coefficients γ and α_B are both functions of temperature. During the virialization process, the gas inside a minihalo is shock heated to the virial temperature. As for the gas outside the halo ($r > r_{\text{vir}}$), since we are looking at high redshifts when reionization is still very patchy, the IGM around a minihalo might be much colder or much hotter than the gas inside the minihalo depending on its environment. In other words, either the minihalo is embedded in an almost neutral region, or it is embedded in an HII region produced by a neighboring galaxy. If we go to high enough redshifts, the probability for the halo to be in a neutral region increases. With an X-ray background, we assume that the temperature of gas around each minihalo equals to T_{IGM} . The HI column density of a minihalo (integrated from $-r_{\text{vir}}$ to $+r_{\text{vir}}$ along a line of sight passing through the halo center) as a function of its mass is shown in Fig.3 for redshift 10. For low mass minihalos, the HI column density increases with the halo mass, but it decreases rapidly for halo masses larger than $\sim 5 \times 10^7 M_{\odot}$, as the gas is gradually ionized in those halos with higher virial temperatures.

Another ingredient for the computation of 21 cm optical depth is the number density of Ly α photons, which is essential for determining the spin temperature of hydrogen. The background Ly α photons can not penetrate into minihalos and contributing to the Ly α flux inside them (see the arguments in section 2.3.3), and in the absence of stars, the Ly α photons could come only from recombinations in the gas itself. The Ly α production rate is

$$\dot{n}_{\text{Ly}\alpha} = (2/3) \alpha_B n_e n_p. \quad (20)$$

The factor of two-thirds accounts for the probability of the recombination leading to a Ly α photon and the other one-third is the probability of obtaining photons of frequencies different from the Ly α (Osterbrock 1989). Because of the extremely large cross-section of Ly α resonant scattering, the Ly α photons cannot escape immediately from the halo, but scatter with the hydrogen atoms

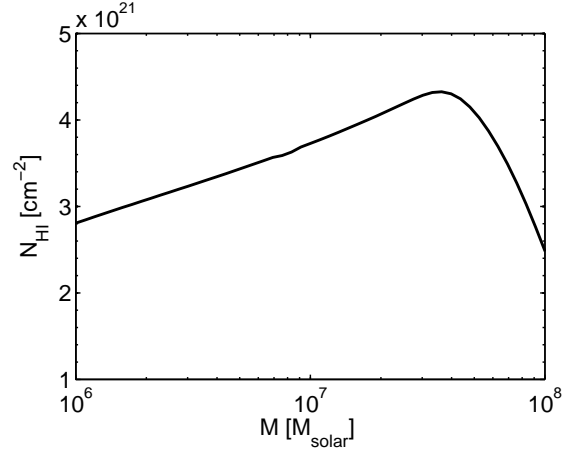


Figure 3. The HI column density as a function of minihalo mass at redshift 10.

frequently and diffuse in the gas. This process is well described as a “random walk”. Thus, the Ly α photons can accumulate in a given region for a diffusion time, $t_{\text{diffu}} = l_{\text{rms}}^2 / (c l_{\text{mfp}})$, where l_{rms} is the r.m.s. distance that Ly α photons have to travel in order to escape from the region, and $l_{\text{mfp}} = (n_{\text{HI}} \sigma_{\alpha} / \Delta\nu_D)^{-1}$ is the mean free path of the Ly α photons. For the case of minihalo $l_{\text{rms}} = r_{\text{vir}}$. However, the Ly α accumulating time t_{acc} is also limited by the time interval between the halo formation and the Hubble time, i.e. $(t_{\text{H}} - t_{\text{F}})$, then the real accumulating time of Ly α photons is $t_{\text{acc}} = \min\{t_{\text{diffu}}, t_{\text{H}} - t_{\text{F}}\}$. Actually, t_{diffu} is quite large, and it is always longer than the Hubble time, so the Ly α photons would accumulate for a time interval $(t_{\text{H}} - t_{\text{F}})$. Due to the large accumulating time, even with a low ionized fraction in the IGM, the Ly α photons from recombination could also be important outside the r_{vir} as compared to the background Ly α photons.

In order to illustrate the relative effects of collisional coupling and Ly α coupling in minihalos, we plot several contours of the coefficients x_c (upper panel) and x_{α} (bottom panel) on $\log(T_{\text{vir}}) - z$ planes in Fig.4. These coefficients are all calculated for the central properties of halos, and to show clearly the dependence of x_{α} on the virial temperature of halos, we set the accumulation time of the Ly α photons to be a Hubble time at each redshift.

As we see clearly from the contours, x_{α} dominates over x_c for high mass halos, in which gas is collisionally ionized and Ly α photons are effectively produced and accumulated from recombinations. On the other hand, x_c dominates over x_{α} for low mass halos which are almost completely neutral.

As for x_{α} , it has a very weak dependence on the redshift, but increases dramatically around $T_{\text{vir}} \sim 10^4 \text{K}$ due to the change of ionized fraction there. At higher temperatures, when the gas is almost collisionally ionized, the x_{α} slowly drops again because of the decreasing α_B with temperature.

There are several effects taking place to determine the behavior of x_c . In general, x_c increases with temperature because of the increasing collisional de-excitation rate κ_{10}^{HH} and κ_{10}^{eH} . At low temperatures, x_c comes mainly from the H-H collisions, and the slowly decreasing x_c with increasing redshift is caused by the decreasing central density of hydrogen in less concentrated minihalos at higher redshifts. The coupling changes from H-H collisions-dominated to e^- -H collisions-dominated as the temperature goes up, and this is in part responsible for the non-monotonic behavior of x_c at $\log(T_{\text{vir}}) \sim 4 - 4.5$. In addition, given a redshift,

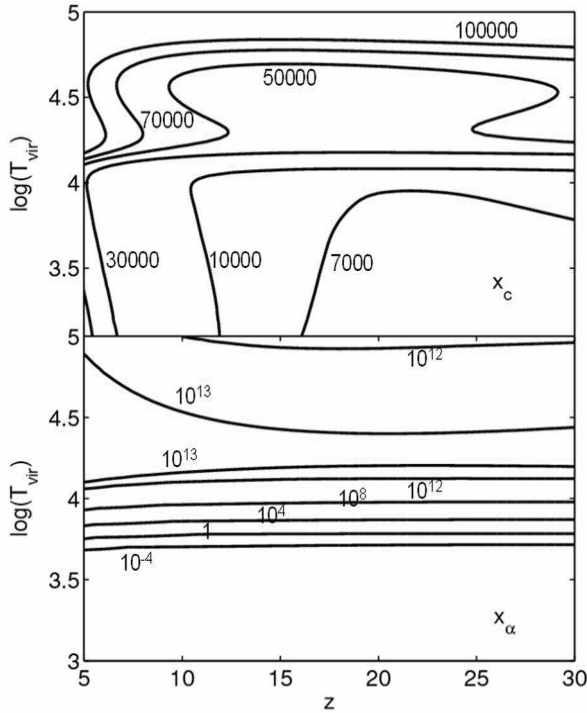


Figure 4. Contours of collisional coupling coefficient x_c (upper panel) and Ly α coupling coefficient x_α (bottom panel) on $\log(T_{\text{vir}}) - z$ planes. From bottom to top in each panel, the values of the contours are 7×10^3 , 10^4 , 3×10^4 , 5×10^4 , 7×10^4 , and 10^5 for x_c , and 10^{-4} , 1 , 10^4 , 10^8 , 10^{12} , 10^{13} , and 10^{13} , and 10^{12} for x_α , respectively.

the concentration is lower for higher mass (higher T_{vir}) halos, and the central density of gas is lower. Therefore, n_e is smaller at high temperatures when the gas is almost ionized and n_e represents the total hydrogen density. This could also result in the non-monotonic behavior of x_c .

2.3.2 Modeling the dwarf galaxies

As discussed in section 2.2, star bursts could occur in some of the halos, turning them into dwarf galaxies when the cooling process allows the gas to cool and collapse within a Hubble time. Depending on the initial mass function (IMF) and star formation efficiency, the stars produce a radiation field that will photonionize the gas creating an HII region, heat the gas around, and produce Ly α photons at the same time. All these effects could have influences on the strength and shape of the 21 cm signal of the galaxy.

The initial mass function and the emission spectrum of the first galaxies remain very uncertain (see Ciardi & Ferrara 2005 for a review). However, Schaerer (2002, 2003) has examined spectral properties of the ionizing continua of high redshift starburst galaxies for various IMFs, metallicities and star formation histories². We make use of their results for the emitting rate of H and He⁺ ionizing photons per solar mass of burst stars, denoted by Q_{H} and Q_{He^+} , as well as the average energy per photon with $E > 54.4\text{eV}$ (He⁺

ionizing threshold) denoted by \bar{E}_{He^+} . The Lyman continuum photons are divided into two parts: photons with $E < 100\text{eV}$ could effectively result in photonionization, and those soft X-rays with $E > 100\text{eV}$ have a large probability to escape, and serve as an extra heating mechanism in addition to the X-ray background outside the HII region. Assuming a simple power law for the high energy tail of the emission spectrum, we extrapolate Q_{He^+} and \bar{E}_{He^+} to get the production rate of soft X-rays Q_{X} and their average photon energy \bar{E}_{X} . Thus the production rate of ionizing photons is $Q_{\text{ion}} = Q_{\text{H}} - Q_{\text{X}}$.

As we are considering an early reionization epoch when the UV background has not been set up, all the ionizing photons creating an HII region come from the stellar sources inside of the dwarf galaxy, i.e. the Q_{ion} . Considering the soft spectra of stellar sources, we assume a sharp boundary for each HII region, i.e. $x_i = 1$ for $r \leq R_{\text{HII}}$, $x_i = \bar{x}_i(z)$ for $r > R_{\text{HII}}$ and $r > r_{\text{vir}}$, and $x_i = x_i(\text{CIE})$ for $R_{\text{HII}} < r \leq r_{\text{vir}}$ when $R_{\text{HII}} < r_{\text{vir}}$. Further, we assume all the stars to be located at the center of the galaxy, and neglect the Hubble expansion during the growth of the HII region, as its growth time is much shorter than the Hubble time. Starting from the star burst time, t_* , the evolution equation of the radius of an HII region is

$$n_{\text{HII}}(R) 4\pi R^2 \frac{dR}{dt} = \dot{N}_\gamma(t) - \int_0^{R(t)} \alpha_{\text{B}} n_e n_p 4\pi r^2 dr, \quad (21)$$

where $\dot{N}_\gamma(t)$ is the ionizing rate, and the second term on the right-hand side accounts for recombinations in the HII region. Here $\alpha_{\text{B}} = \alpha_{\text{B}}(10^4\text{K}) = 2.59 \times 10^{-13}\text{cm}^3\text{s}^{-1}$ is used, as appropriate for the temperature of an ionized region. Here we neglect the change in gas density profile due to the heating, as we will see later that it is quite weak. Before the ionizing front breaks out of the virial radius, the ionization is caused by ionizing photons that did not escape the galaxy, then

$$\dot{N}_\gamma(t) = (1 - f_{\text{esc}}) Q_{\text{ion}} f_\star \frac{\Omega_b}{\Omega_m} M, \quad (22)$$

where f_{esc} is the escape fraction of ionizing photons, and f_\star is the star formation efficiency normalized to the cosmic baryon content associated with a halo of mass M . We use $f_{\text{esc}} = 0.07$ as favored by the early reionization model (ERM, Gallerani et al. 2008), and a mass-dependent f_\star provided by the handy fit in Salvadori & Ferrara (2009). After the ionizing front grows larger than the virial radius, all the ionizing photons have escaped, then $f_{\text{esc}} = 1$, and

$$\dot{N}_\gamma(t) = f_{\text{esc}} Q_{\text{ion}} f_\star \frac{\Omega_b}{\Omega_m} M. \quad (23)$$

We plot the radius of the HII region as a function of the time after star burst for a dwarf galaxy with $M = 10^7 M_\odot$ at redshift 10 in Fig.5. The (physical) virial radius of this galaxy is $r_{\text{vir}} = 641\text{pc}$. Since Q_{H} has a weak dependence on the metallicity but very sensitive to the IMF, we fix the metallicity at $Z = 10^{-7}$, and show the growth of R_{HII} for three different IMFs. These IMF models are correspondingly chosen after Schaerer (2002, 2003), with a power-law slope of the Salpeter value ($\alpha = 2.35$) and different upper and lower mass limits: $1 - 100 M_\odot$ (IMF-A), $1 - 500 M_\odot$ (IMF-B), and $50 - 500 M_\odot$ (IMF-C). The R_{HII} grows very fast at the beginning, but limited by the speed of light. At later stages, it is also limited by the stellar lifetime. As the stars fade away, the subsequent supernova explosions will sweep the surrounding gas away, thus suppressing the 21 cm absorption signal. For this reason we stop the evolution of the HII radius at its maximum value. As one could

² Data are available at:
<http://cdsarc.u-strasbg.fr/cgi-bin/Cat?VI/109>

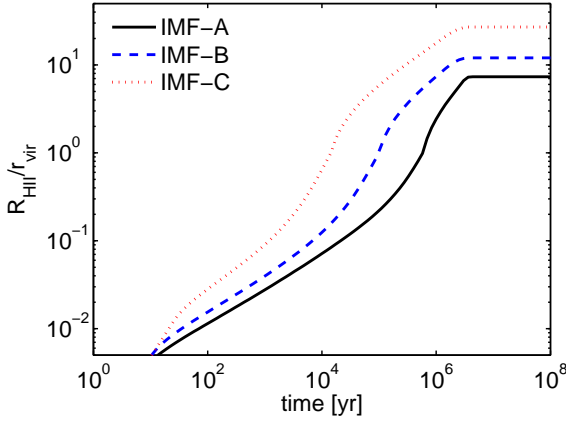


Figure 5. The growth of R_{HII} for a dwarf galaxy with mass $M = 10^7 M_\odot$ and redshift $z = 10$ after a star burst. The solid (black), dashed (blue), and dotted (red) curves are for IMF-A ($1 - 100 M_\odot$), IMF-B ($1 - 500 M_\odot$), and IMF-C ($50 - 500 M_\odot$), respectively. All the IMF models have a Salpeter shape, the metallicity shown here is $Z = 10^{-7}$, and we set $f_X = 0.1$ for the X-ray background.

expect, the size of an HII region is very sensitive to the IMF due to the strong dependence of Lyman continuum production on stellar mass. Here we are considering isolated HII regions around dwarf galaxies, but in reality the galaxies will be somewhat clustered. So the ionized regions may extend further. However, the clustering of the first galaxies is beyond the scope of this work, and we reserve this to future works.

Once an HII region is created, the gas inside rapidly approaches the temperature around $2 \times 10^4 \text{ K}$ (Meiksin 2007). For the 21 cm absorption which requires neutral hydrogen, it is more important to compute the gas temperature outside the HII region. Here we include the heating by local soft X-rays emitted by the dwarf galaxies. While the stars in the galaxy are also emitting Ly α photons, the heating effect due to the repeated Ly α scattering is negligible (Chen & Miralda-Escudé 2004). So the evolution of gas temperature can still be described by Eq.(12), but with an extra contribution to the $\epsilon_{\text{X,h}}$ from the local X-rays. The energy deposition rate of local soft X-ray heating is

$$\epsilon_{\text{X,g}} = \mathcal{R} n_{\text{HI}} (\bar{E}_{\text{X}} - E_{\text{th}}) f_{\text{X,h}}, \quad (24)$$

where \mathcal{R} is the ionizing rate by the soft X-rays, $E_{\text{th}} = 13.6 \text{ eV}$ is the ionization threshold of hydrogen, and $f_{\text{X,h}}$ is the fraction of the primary electron energy deposited into heat. The X-ray ionizing rate can be written as $\mathcal{R} = Q_{\text{X}}(t) M_* \sigma_{\text{I}}(\nu) / (4\pi r^2)$, where $M_* = f_* (\Omega_b / \Omega_m) M$, and $\sigma_{\text{I}}(\nu)$ is the photonionization cross section of hydrogen (Meiksin 2007):

$$\sigma_{\text{I}}(\nu) = \sigma_0 \left[\beta \left(\frac{\nu}{\nu_{\text{th}}} \right)^{-s} + (1 - \beta) \left(\frac{\nu}{\nu_{\text{th}}} \right)^{-s-1} \right], \quad (25)$$

where $\sigma_0 = 6.30 \times 10^{-18} \text{ cm}^2$, $\nu_{\text{th}} = 3.290 \times 10^{15} \text{ Hz}$ corresponding to the ionization threshold 13.6 eV , $\beta = 1.34$, and $s = 2.99$. The average frequency of photons with $E \geq 0.1 \text{ keV}$ is used here. As for $f_{\text{X,h}}$, we use a handy fit by Valdés & Ferrara (2008), which is a function of ionized fraction x_i .

With the initial condition of the IGM temperature at the star burst time, we solve for the gas temperature around an HII region, and plot the results for a dwarf galaxy with $M = 10^7 M_\odot$ at redshift 10 in Fig.6. We take $f_X = 0.1$ as the fiducial value for the

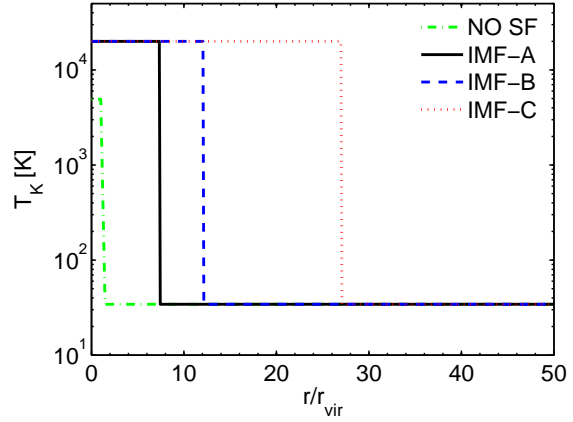


Figure 6. The temperature profiles of gas around a dwarf galaxy with mass $M = 10^7$ and metallicity $Z = 10^{-7}$ at redshift $z = 10$. The solid (black), dashed (blue), and dotted (red) curves are for Salpeter IMFs with mass ranges of $1 - 100 M_\odot$ (IMF-A), $1 - 500 M_\odot$ (IMF-B), and $50 - 500 M_\odot$ (IMF-C), respectively. The temperature profile of gas if there is no star formation is also plotted with the dot-dashed (green) curve, and a fiducial value of $f_X = 0.1$ is assumed for the X-ray background.

X-ray background. The solid, dashed, and dotted curves are for the three IMF models used in Fig.5. For illustration, we have assumed that the star burst occurred at the same time as the halo formation, and the temperatures are all evaluated at $t_{\text{value}} = t_{\text{H}} - t_{\text{F}}$, where the most probable value for z_{F} is used. For comparison, the temperature profile for a starless minihalo of the same mass and redshift is also shown as the dot-dashed line. Inside the HII region, the temperature is fixed at $2 \times 10^4 \text{ K}$, and it drops down very sharply at the ionizing front due to the lower heating rate outside, as we could expect for stellar sources. The main heating mechanism outside r_{vir} is the X-ray background heating.

Apart from ionizing photons and soft X-rays, the dwarf galaxy is also producing Ly α photons which are essential for determining the spin temperature of hydrogen. However, those Ly α photons directly emitted by the galaxy could hardly contribute to the coupling in the gas outside the HII region due to the extremely long diffusion time, and they will be blocked near the ionization front. It is the Ly α photons cascaded from soft X-rays that penetrate into the nearby IGM and effectively couple the spin temperature to the kinetic temperature of the gas (Chen & Miralda-Escudé 2008). So the contributing Ly α photons near an HII region come from recombination, the Ly α background, as well as the soft X-ray cascading. Valdés & Ferrara (2008) have examined the fraction $f_{\text{Ly}\alpha}$ of the primary energy of electrons ionized by X-rays that converts into Ly α radiation. Using their result, the Ly α production rate from cascading around the HII region is

$$\dot{n}_{\text{Ly}\alpha} = \mathcal{R} n_{\text{HI}} \frac{\bar{E}_{\text{X}} - E_{\text{th}}}{h\nu_{\alpha}} f_{\text{Ly}\alpha}, \quad (26)$$

where $\nu_{\alpha} = 2.47 \times 10^{15} \text{ Hz}$ is the frequency of Ly α photons. The total number density of Ly α photons is obtained by integrating $\dot{n}_{\text{Ly}\alpha}$ over an accumulating time t_{acc} .

In this case, the accumulating time of Ly α photons is $t_{\text{acc}} = \min\{t_{\text{diffu}}, t_{\text{Xray}}, (t_{\text{H}} - t_{\text{s}})\}$, where t_{diffu} is the Ly α diffusion time as before, but we take the mean free path (m.f.p.) of the soft X-rays as the l_{rms} here. t_{Xray} is the time during which the dwarf galaxy is producing X-rays, and $(t_{\text{H}} - t_{\text{s}})$ is the time interval between the halo redshift and the star burst redshift. Because of the large m.f.p.

of the X-rays (compared to the r_{vir}), the $\text{Ly}\alpha$ diffusion time is also very large in this case, even larger than the Hubble time. As a result, the $\text{Ly}\alpha$ accumulating time is determined by $(t_{\text{H}} - t_{\text{s}})$ for the cases with IMF-A and IMF-B, while for the case with IMF-C, the $\text{Ly}\alpha$ accumulating time is limited by the lifetime of the stars.

2.3.3 The $\text{Ly}\alpha$ background

In addition to the $\text{Ly}\alpha$ photons produced by recombination and those cascaded $\text{Ly}\alpha$ photons near galaxies, there is also a $\text{Ly}\alpha$ background. The $\text{Ly}\alpha$ background originates from the continuum photons to the blue side of the $\text{Ly}\alpha$ line emitted by the early galaxies, and its intensity becomes important at very high redshift (Chen & Miralda-Escudé 2008). Only photons with $\nu < \nu_{\beta}$ can be redshifted to ν_{α} , and all photons of higher frequencies will be absorbed at the $\text{Ly}\beta$ or higher resonance Lyman series lines. Let $E(\nu)$ be the number of photons emitted over stars' lifetime per baryon in one of the halos that collapse to form stars and per unit of frequency. According to the stellar spectra we adopted from Schaerer (2003), $E(\nu)$ is well approximated as flat near the $\text{Ly}\alpha$ frequency, then the intensity of the continuum $\text{Ly}\alpha$ background can be written as (Chen & Miralda-Escudé 2008)

$$J_{\alpha} = \tilde{J}_0 \bar{E}_{\alpha} \nu_{\alpha} [F(z) - F(z_{\beta})]. \quad (27)$$

Here \tilde{J}_0 is the fiducial $\text{Ly}\alpha$ intensity corresponding to a photon density of one photon per hydrogen atom per log frequency,

$$\tilde{J}_0 = \frac{c n_{\text{H}}}{4\pi \nu_{\alpha}}, \quad (28)$$

where n_{H} is the number density of hydrogen. $\bar{E}_{\alpha} = \bar{E}(\nu_{\alpha})$ is averaged over all the galaxies in the mass range of our consideration, and we estimate this value from the spectrum data provided by Schaerer (2003). In Eq.(27), $F(z)$ is the fraction of mass bound in star-forming halos,

$$F(z) = \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{M}{\bar{\rho}_0} n(M, z) p_{\star}(M, z) dM, \quad (29)$$

where $n(M, z)$ is the halo mass function and $p_{\star}(M, z)$ is the probability of having star formation for a halo with mass M at redshift z . We derive $p_{\star}(M, z)$ according to the star formation criterion given in Section 2.2. At $z = 20$, $J_{\alpha} \approx 3 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$, while at $z = 10$, it has increased to $J_{\alpha} \approx 2 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$ which is already important for the Wouthuysen-Field coupling effect.

The problem of $\text{Ly}\alpha$ background propagating into minihalos is complicated. The situation in minihalos would be different from that in the IGM because of their higher column densities of neutral hydrogen (typically, $N_{\text{HI}} \sim 10^{21} \text{ cm}^{-2}$). The $\text{Ly}\alpha$ scattering cross section in a region of high density consists of a Doppler core with a typical width of $\Delta\nu_{\text{D}} = b/\lambda_{\alpha}$ centered on the $\text{Ly}\alpha$ frequency, and Lorentzian wings outside the core. Once a photon is redshifted or scattered into the “core” frequencies, the cross section is large and its mean free path becomes very short and is spatially confined within a small region with very long diffusion time. Thus, the photons which eventually make up the $\text{Ly}\alpha$ background come from the blue side of the $\text{Ly}\alpha$ line, at the edge of the “core” and “wing”. In the case of minihalo, however, these photons would be blocked at the surface of the minihalo. The redshift across the minihalo is also too small for bluer wing photons which is not blocked at the edge of the minihalo to get redshifted into the core-wing boundary region when they arrive at the center of the halo.

Another possibility is to consider photons with such frequency

that their optical depth through the minihalo is about 1. Such a photon would scatter once inside the halo. One scattering per photon is of course negligible for the coupling effect in itself, but the frequency of the photon would be changed after the scattering. If the frequency increases, then the photon cross section become even smaller and would escape right away, but if the photon loses energy during the collision and shifts to lower frequency, the cross section would be increased. Could such a change bring the photon from the “wing” to the “core”? The frequency ν of such a wing photon is given by $N_{\text{HI}}(r_{\text{vir}}) \sigma_{\alpha}(\nu) = 1$, where $N_{\text{HI}}(r_{\text{vir}})$ is the column density of the minihalo from r_{vir} to its center, and $\sigma_{\alpha}(\nu)$ is the scattering cross section on the $\text{Ly}\alpha$ damping wing. For typical thermal velocity of the H atom in the minihalo, we estimate that the change of photon frequency in one scattering $d\nu < 2.2 \times 10^{11} \text{ Hz}$, comparable to the size of the core. On the other hand, the frequency distance to the line center for such a photon is $(\nu - \nu_{\alpha}) \sim 10^{13} \text{ Hz}$, so $d\nu \sim 1\%(\nu - \nu_{\alpha})$. Therefore, during one or even a few favorable scatterings the photon could not enter the core and should escape away. We conclude that with the exception of the surface, the $\text{Ly}\alpha$ background could not affect the spin temperatures of the minihalos.

3 THE 21 CM LINE PROFILES

With the detailed models of gas density, velocity profile, ionization state, temperature evolution, and the intensity of both local and global $\text{Ly}\alpha$ photons for the minihalos and the dwarf galaxies described above, we are now ready to compute their spin temperature profiles and 21 cm optical depths. In this section, we show our results of these detailed profiles for a variety of parameters. Although it will be very challenging to resolve them with radio instruments in the near future, these analyses help us explore the physical origins of the line profiles and understand the physics behind.

3.1 The Coupling Effects and Spin Temperature

In Fig.7, we plot the spin temperature as a function of distance from the halo center for a minihalo (left panel) and a dwarf galaxy (right panel) of the same mass $M = 10^7 M_{\odot}$ at redshift $z = 10$. We have taken $f_{\text{X}} = 0.1$ as the fiducial value for the X-ray background. In order to show the coupling effects, the kinetic temperature of the gas and the CMB temperature are also plotted. As we see clearly from the left panel, the spin temperature of the minihalo is coupled to the gas kinetic temperature (T_{vir} of the halo) at the center. The halo with $M = 10^7 M_{\odot}$ and $z = 10$ has $T_{\text{vir}} \sim 5000 \text{ K}$, and the gas is almost neutral in collisional ionization equilibrium. As a result, the $\text{Ly}\alpha$ photons from recombination is totally negligible and the collisional coupling dominates. As the radius increases, the collisional coupling becomes less and less effective because of the decreasing density, and the spin temperature gradually decouples from the kinetic temperature. In addition to the dropping density, the collisional de-excitation rate coefficients (κ_{10}^{eH} and κ_{10}^{HH}) also decrease due to the sharply decreasing kinetic temperature outside r_{vir} , dramatically reducing the collisional coupling effect. However, the $\text{Ly}\alpha$ background at $z = 10$ is already strong enough to couple the spin temperature closely to the kinetic temperature of the gas. And the recombination in the IGM also produces a significant amount of $\text{Ly}\alpha$ photons. As a result, T_{S} is always coupled to T_{K} outside minihalos at $z = 10$.

As for the spin temperature profile of the dwarf galaxy in the right panel of Fig.7, the IMF model-A and a metallicity of

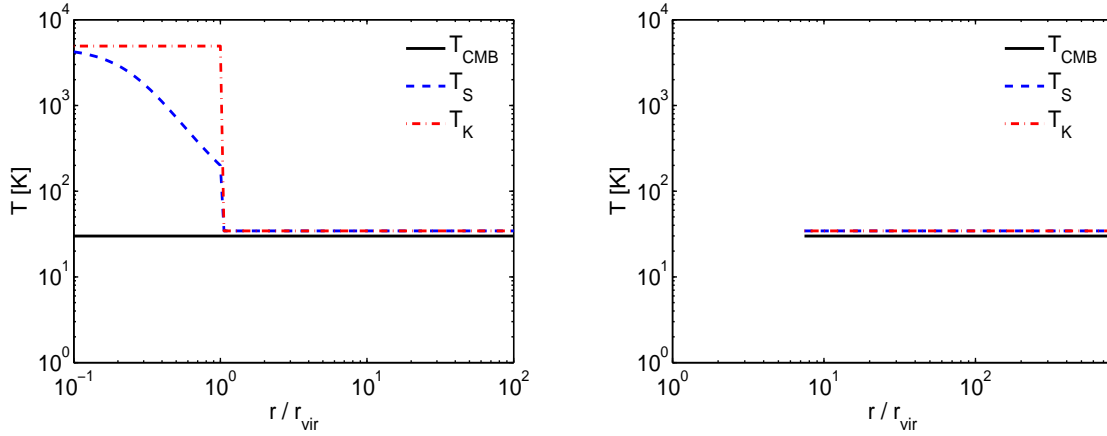


Figure 7. Spin temperature (dashed lines) and kinetic temperature (dot-dashed lines) profiles of a minihalo/dwarf galaxy with mass $M = 10^7 M_{\odot}$ at redshift 10. A fiducial value of $f_{\text{X}} = 0.1$ is assumed for the X-ray background. The solid curves represent the CMB temperature. *Left:* the case for a minihalo in CIE. *Right:* the case for a dwarf galaxy which is photonized after a star burst with IMF model-A and metallicity $Z = 10^{-7}$. The temperature curves are cut at the HII radius of $7.02 r_{\text{vir}}$.

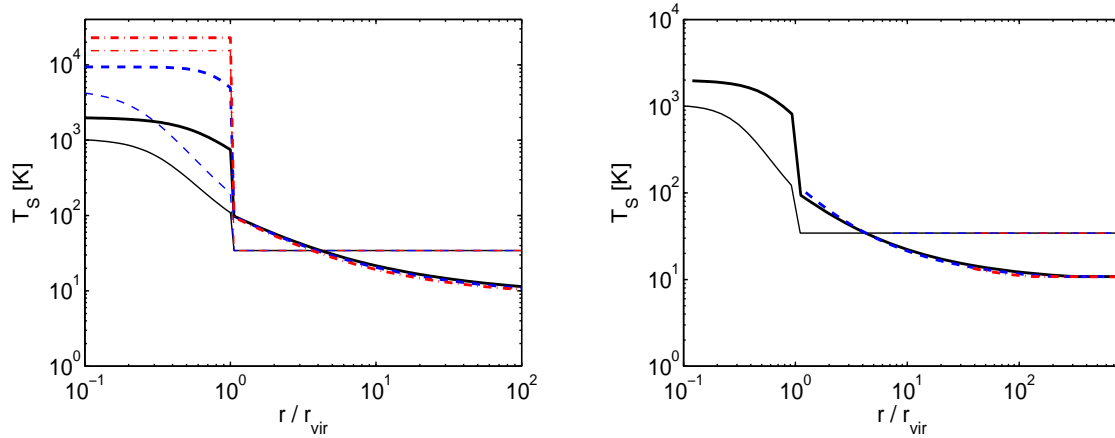


Figure 8. Spin temperature profiles of minihalos/dwarf galaxies of different masses: $M = 10^6 M_{\odot}$ (solid curves), $M = 10^7 M_{\odot}$ (dashed curves), and $M = 10^8 M_{\odot}$ (dot-dashed curves), respectively. A fiducial value of $f_{\text{X}} = 0.1$ is assumed for the X-ray background. The set of thick curves is for redshift 20, and the set of thin curves is for redshift 10. *Left:* the case for minihalos in CIE. *Right:* the case for dwarf galaxies that are photonized after a star burst with IMF model-A and metallicity $Z = 10^{-7}$.

$Z = 10^{-7}$ are assumed. We stop the R_{HII} and T_{K} evolution at $t_{\text{value}} = t_{\text{H}} - t_{\text{F}}$, where t_{F} is the most probable formation time of this halo, and the spin temperature is also evaluated at this time. The left-hand side cut-offs of these curves are just the position of R_{HII} ($7.02 r_{\text{vir}}$). As the HII radius of this galaxy is larger than the virial radius, the low density and low temperature outside the HII region make the collisional coupling very weak. In this case, the $\text{Ly}\alpha$ pumping is always the dominating coupling effect. The global $\text{Ly}\alpha$ photons from recombination and background flux dominate over the local $\text{Ly}\alpha$ photons from soft X-ray cascading, and just as the case outside a minihalo, the spin temperature sticks to the gas kinetic temperature.

Then we investigate how the spin temperature changes with halo mass and redshift, and plot two sets of curves for various halo masses in Fig.8, one (the thin set) for $z = 10$, and the other (the thick set) for $z = 20$. A fiducial value of $f_{\text{X}} = 0.1$ is assumed here. For the minihalos in the left panel, the spin temperature is closely coupled to the kinetic temperature outside the r_{vir} for halos at $z =$

10, in part because of the $\text{Ly}\alpha$ background, and in part because of the accumulated $\text{Ly}\alpha$ photons from recombination in the IGM that is partially ionized by the X-ray background. But at $z = 20$, both the $\text{Ly}\alpha$ background and the X-ray background are still weak, and T_{S} lies between the T_{CMB} and T_{K} for gas around minihalos at this redshift. Inside the halos, the density is larger at higher redshift, and the collisional coupling effect is correspondingly stronger, so the spin temperature is more tightly coupled to the virial temperature. On the other hand, halos are more concentrated at lower redshift, and the slope of gas density profile is steeper. As a result the spin temperature drops more rapidly with radius at lower redshift. One different feature for the $10^8 M_{\odot}$ halo is that its spin temperature is effectively coupled to the gas kinetic temperature out to r_{vir} , because for this relatively high mass halo, its virial temperature ($\sim 1.5 \times 10^4 \text{K}$ for $z = 10$, and $\sim 2.3 \times 10^4 \text{K}$ for $z = 20$) is high enough to make the gas collisionally ionized ($x_i \sim 52\%$ for $z = 10$, and $x_i \sim 98\%$ for $z = 20$). With this partially ionized

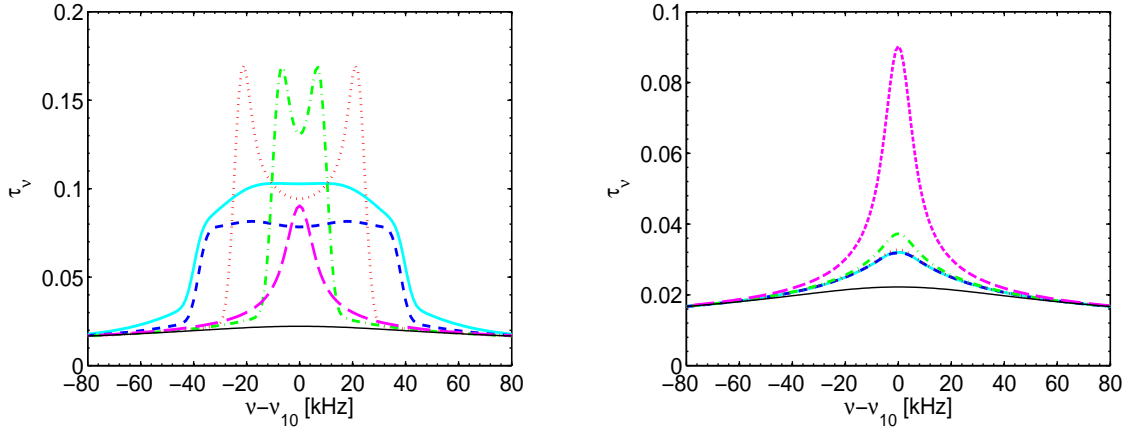


Figure 9. Optical depth profiles of a minihalo/dwarf galaxy with mass $M = 10^7 M_\odot$ at redshift 10. All the curves take $f_X = 0.1$. The impact parameters of the thick curves are $\alpha = 0$ (solid cyan), 0.3 (short-dashed blue), 1 (dotted red), 3 (dot-dashed green), and 10 (long-dashed magenta), respectively, and the thin solid black curve is for $\alpha = 30$. *Left:* the case for a minihalo in CIE. *Right:* the case for a dwarf galaxy which is photonized after a star burst with IMF model-A and metallicity $Z = 10^{-7}$.

gas, Ly α photons from recombinations are effectively trapped, and serve as a strong coupling agent.

In the right panel of Fig.8, the spin temperature profiles for dwarf galaxies are all cut off at their HII radii at the left-hand side. For the case of $10^6 M_\odot$ dwarf galaxy, due to the much lower star formation efficiency ($f_* \sim 4 \times 10^{-5}$, which increases to ~ 0.03 for a galaxy with $10^8 M_\odot$) (Salvadori & Ferrara 2009), it could only create a very small HII region ($R_{\text{HII}} \sim 0.008 r_{\text{vir}}$ for $z = 10$, and $R_{\text{HII}} \sim 0.02 r_{\text{vir}}$ for $z = 20$). As for the galaxies with $10^7 M_\odot$ and $10^8 M_\odot$, they have larger stellar masses and create larger HII regions. So they have much less gas which could contribute to the 21 cm line absorption.

3.2 The Absorption Line Profiles

Consider an isolated minihalo with mass $M = 10^7 M_\odot$ at redshift $z = 10$ for which we compute the optical depth as a function of frequency using Eq.(14). Results are shown in the left panel of Fig.9 for different impact parameters of the lines of sight. Very interesting features can be seen in the shown profiles. First, there are two peaks which sandwiched the center of the line for impact parameters $\alpha = 1$ and $\alpha = 3$, showing horn-like profiles; second, as the impact parameter increases, the peak optical depth is NOT always decreasing. These two points are related issues, and they are both caused by the infalling gas with low spin temperature outside the minihalo.

To see clearly the origin of these interesting profiles, we have to understand the different contributions to the 21 cm absorption from the gas located at different radii. Because of the infall, the absorption line produced by the gas at the far side of the halo is blue-shifted, while that produced by the gas at the near side of the halo is redshifted. Let $\nu_p(r)$ be the peak frequency of optical depth created by gas located at radius r , and according to the integrand in Eq.(14), the absorption is shifted from the line center by

$$\nu_p(r) - \nu_{10} = \frac{\bar{v}(r)}{c} \nu_{10}. \quad (30)$$

Considering a line of sight passing through a minihalo with $M = 10^7 M_\odot$ and $z = 10$ from the center ($\alpha = 0$), we divide the integration into segments, each of which has a contribution from a length

of $1 r_{\text{vir}}$ on the line of sight. Then we plot every absorption line created by one segment in Fig.10. In the upper panel, the absorption line produced by the gas inside of r_{vir} is shown as the dashed curve, the solid lines from right to left correspond to the absorptions by segments of $(1 - 2) r_{\text{vir}}$, $(2 - 3) r_{\text{vir}}$, $(3 - 4) r_{\text{vir}}$, $(4 - 5) r_{\text{vir}}$, $(5 - 6) r_{\text{vir}}$, and $(6 - 7) r_{\text{vir}}$, respectively, and the dotted-dashed line represents the absorption by the segment of $(7 - 8) r_{\text{vir}}$. In the bottom panel, the 12 solid lines from left to right correspond to the absorptions by segments of $1 r_{\text{vir}}$ each starting from $8 r_{\text{vir}}$, and the last curve on the right represents the integral absorption from 20 to $100 r_{\text{vir}}$.

As seen clearly from Fig.10, the virialized gas inside the minihalo has no bulk velocity, and the peak optical depth is located at the center. The gas at $(1 - 2) r_{\text{vir}}$ has the highest infall velocity, and the corresponding profile lies at the largest distance to the line center in the upper panel. As the radius increases, the τ_ν profile gets closer to the line center because of the lower infall velocity, and the optical depth decreases slowly with the decreasing density. One interesting feature is that there is a special position where the total velocity of the gas changes from negative (infall dominated) to positive (Hubble flow dominated), and at this turning point the two absorption lines created by the two segments on both sides of the minihalo converge into one at the line center, and they contribute substantially to the central optical depth. For the minihalo with $M = 10^7 M_\odot$ and $z = 10$, this turning point lies at $7.3 r_{\text{vir}}$, and consequently the absorption by the segment of $(7 - 8) r_{\text{vir}}$ peaks at the line center. After that, the τ_ν profiles that come from larger radii leave the line center again, because the infall velocity becomes even smaller and the total velocity (in the same direction as Hubble flow) becomes more and more positive. Finally, when it goes out of the region influenced by the minihalo's gravity, and the density drops to the cosmic mean value, we recover the IGM optical depth.

The line profiles in Fig.9 are better understood by noting that each is an integral of contributions from different radii. A substantial contribution to the optical depth comes from the outer region, because the gas outside r_{vir} has lower spin temperature. Especially, the gas in the infalling region on the far (near) side of the halo shares the same bulk velocity with the gas out of the region on the near (far) side, and they absorb the 21 cm photons at the same

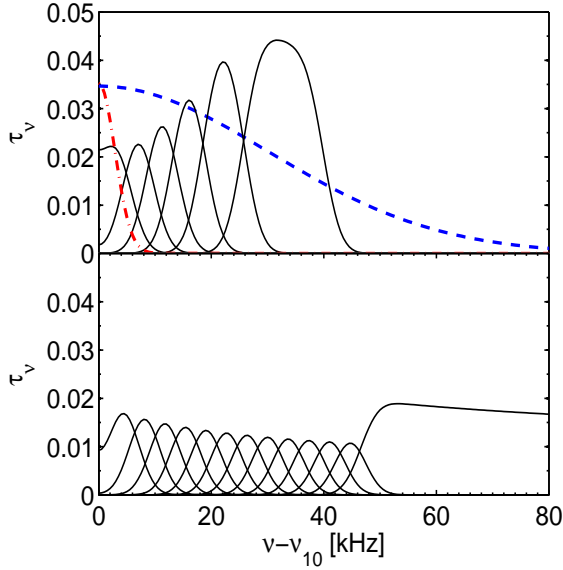


Figure 10. Different contributions to the optical depth from the gas at different radii. *Upper panel:* the absorption by gas inside of r_{vir} is shown as the dashed line, the solid lines from right to left correspond to the absorptions by segments of $(1-2)r_{\text{vir}}$, $(2-3)r_{\text{vir}}$, $(3-4)r_{\text{vir}}$, $(4-5)r_{\text{vir}}$, $(5-6)r_{\text{vir}}$, and $(6-7)r_{\text{vir}}$, respectively, and the dotted-dashed line represents the absorption by the segment of $(7-8)r_{\text{vir}}$. *Bottom panel:* the 12 solid lines from left to right correspond to the absorptions by segments of $1 r_{\text{vir}}$ each starting from $8 r_{\text{vir}}$, and the last curve represents the integral absorption from 20 to $100 r_{\text{vir}}$.

frequency. Therefore, the optical depth at the frequency range corresponding to the infalling region is increased a lot. In addition, the line profile gets narrower with lower temperature compared to the gas inside the halo, which further increases the peak value. As the impact parameter α increases from 0 to 1, more contribution comes from this cold region, so the peak optical depth increases. Also, the infall velocity shifts the peaks away from the center, and results in the horn-like profile. As α increases further up to 3, the infall velocity decreases, and the two peaks move closer to each other. For α larger than the radius of the velocity turning point, the two peaks merge together and decrease slowly to the IGM optical depth as $\alpha \rightarrow \infty$.

The 21 cm profiles for an isolated dwarf galaxy for various impact parameters are shown in the right panel of Fig.9. Just as before, the spin temperature and the optical depth profiles are all evaluated at the time $t_{\text{value}} = t_{\text{H}} - t_{\text{F}}$, and the most probable value for z_{F} is used. Thus we get an upper limit on the ionization, heating, and $\text{Ly}\alpha$ coupling effects. The line profiles are completely different from the case of minihalos. The horn-like profiles disappears and the absorption is strongly reduced for small impact parameters. The dwarf galaxy with $M = 10^7 M_{\odot}$ and $z = 10$ has an HII radius of $7.3 r_{\text{vir}}$, which is close to the turning point of the gas velocity. In other words, the hydrogen atoms inside r_{vir} and those within the infalling region are totally ionized, erasing the absorption features contributed by hydrogen in this region. Therefore, there will be only one peak at the center no matter what the impact parameter is, and the optical depth is reduced for lines of sight which penetrate the HII region. As the impact parameter α increases, the optical depth first increases because more neutral gas near the HII region is intercepted by the line of sight. It reaches a

maximum when $\alpha \approx R_{\text{HII}}$ and then drops, approaching the IGM optical depth.

We also show the optical depth profiles for different halo masses and redshifts in Fig.11. Here we also take $f_{\text{X}} = 0.1$ for the X-ray background. In the left panel, the case for minihalos is shown. As we expected, the line profiles are broader for halos with greater masses. That is because, on one hand, the virial temperature is higher for halos of greater masses, which results in a broader Doppler profile for the absorption by gas inside the halo, and on the other hand, more massive halos have stronger gravitational influence on the surrounding gas, and the induced higher infalling velocity shifts the absorption line farther from the line center. In general, the absorption is stronger at higher redshift. The reason is that the IGM is denser at higher redshift, and also, the X-ray background is gradually set up as redshift decreases, and it heats and partially ionizes the gas in the IGM. As the frequency gets far from the line center, the optical depths of all the minihalos approach to the mean IGM value.

In the right panel of Fig.11, we show the 21 cm line profiles for dwarf galaxies with the same masses and redshifts as those for minihalos in the left panel. Star bursts with IMF model-A and metallicity $Z = 10^{-7}$ are assumed. An interesting feature emerges for the galaxy with $10^8 M_{\odot}$. Because of the higher star formation efficiency associated with higher mass galaxies, this dwarf galaxy creates a large HII region ($R_{\text{HII}} \sim 38 r_{\text{vir}}$ for $z = 10$, and $R_{\text{HII}} \sim 34 r_{\text{vir}}$ for $z = 20$) erasing all the absorption inside of it. As a result, a broad optical depth trough is produced instead of an absorption line! In the case of IMF model-C, the dwarf galaxy of the same mass could ionize an even larger HII region and hence could result in an even broader optical depth trough.

All the line profiles above are computed assuming that the minihalo or the dwarf galaxy is isolated. In real cosmic structures, a halo is surrounded by other halos, and if we integrate the optical depth to a distance larger than the mean separation D of the halos, we will probably hit another halo. So the integration should only be considered as reliable up to a distance of $D/2$. In practice, a $10^8 M_{\odot}$ halo, for example, might have many smaller halos closer to it than another $10^8 M_{\odot}$ halo. Therefore, it is the mean separation of the smallest halos we are considering, i.e. the halos with $M = 10^6 M_{\odot}$ (for $f_{\text{X}} \lesssim 0.2$), that determines the integration limit. We denote this mean separation as D_{min} . The maximum impact parameter of a line of sight should also be $\alpha_{\text{max}} = D_{\text{min}}/2$. Integrating the optical depth up to $D_{\text{min}}/2$, we plot optical depth profiles of a minihalo (blue dashed curve) and a dwarf galaxy (black solid curve) with $M = 10^7 M_{\odot}$ at $z = 10$ in Fig.12. The line of sight is assumed to be passing through the minihalo/dwarf galaxy from the center, and we set $f_{\text{X}} = 0.1$. We see that the dwarf galaxy only produces a narrow and weak absorption line at the center, because for this galaxy, only the gas in a sphere between the HII radius ($\sim 7.3 r_{\text{vir}}$) and $D_{\text{min}}/2$ ($\sim 9.1 r_{\text{vir}}$) contributes to the absorption. In reality, however, the optical depth will not drop to zero at the boundaries of the absorption line but will connect with another line created by a neighboring halo. In addition, as we mentioned before, the clustering of dwarf galaxies will extend their HII regions. Similarly, some minihalos will be clustered around the dwarfs, and the surrounding gas in the infall region may be ionized, even if the minihalos themselves can self-shield. Therefore, the clustering can reduce the 21 cm optical depth of some minihalos and dwarf galaxies. Although the problem should ideally include the clustering properties of early galaxies, it is beyond the scope of this paper to include such features.

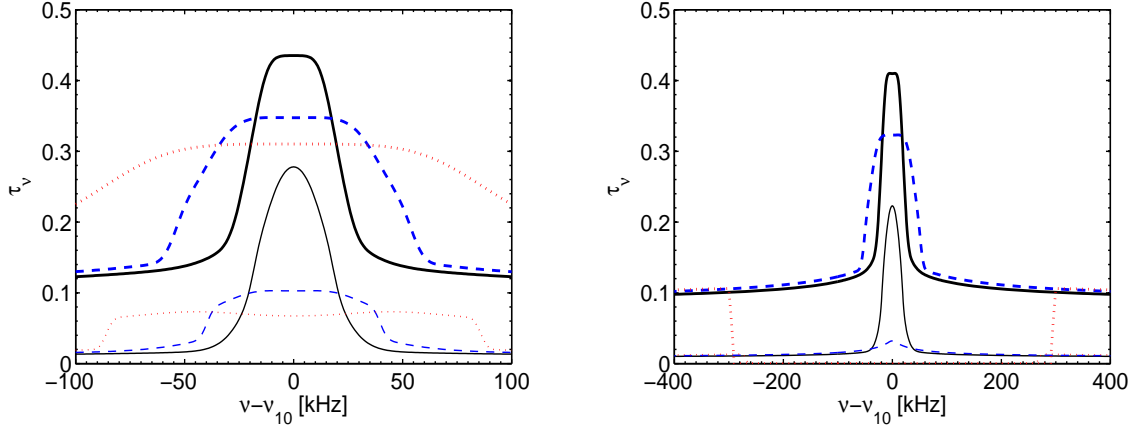


Figure 11. Optical depth profiles of minihalos/dwarf galaxies with different masses: $M = 10^6 M_\odot$ (solid curves), $M = 10^7 M_\odot$ (dashed curves), and $M = 10^8 M_\odot$ (dotted curves), respectively. The thick curves are for redshift 20, while the thin curves are for redshift 10. All the curves take $f_X = 0.1$. *Left:* the case for minihalos in CIE. *Right:* the case for dwarf galaxies that are photonized after a star burst with IMF model-A and metallicity $Z = 10^{-7}$. The impact parameter shown here is $\alpha = 0$.

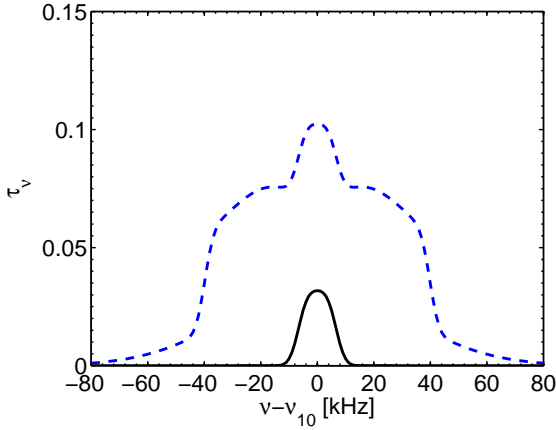


Figure 12. The optical depth profiles of a minihalo (blue dashed curve) and a dwarf galaxy (black solid curve) with $M = 10^7 M_\odot$ at $z = 10$. A star burst with IMF model-A and metallicity $Z = 10^{-7}$ is assumed for this galaxy. The optical depth at each point is integrated up to $D_{\min}/2$, the impact parameter is $\alpha = 0$, and the X-ray parameter is $f_X = 0.1$.

4 THEORETICAL SPECTRUM

In order to superimpose the 21 cm absorption lines of minihalos and dwarf galaxies onto a radio spectrum of GRB afterglow, we first have to compute the line number density per unit redshift. Theoretically, including all (weak and strong) absorption lines, the number of halo intersections along a line of sight per redshift interval is

$$\frac{dN}{dz} = (1+z)^2 \frac{dr}{dz} \int_{M_{\min}}^{M_{\max}} n(M, z) A_{\max} dM, \quad (31)$$

where dr/dz is the comoving radial distance per redshift interval, $n(M, z)$ is the halo mass function given by Eq.(1), and $A_{\max} = \pi \alpha_{\max}^2$ is the cross-section (in physical coordinates) of a halo, in which the maximum impact parameter α_{\max} is set by half of the mean halo separation, i.e. $D_{\min}/2$, at each redshift. We plot the line number density as a function of redshift in Fig.13 for three different values of M_{\min} , which are appropriate for different levels of the X-ray background. The curves are cut off at redshift $z = 8$

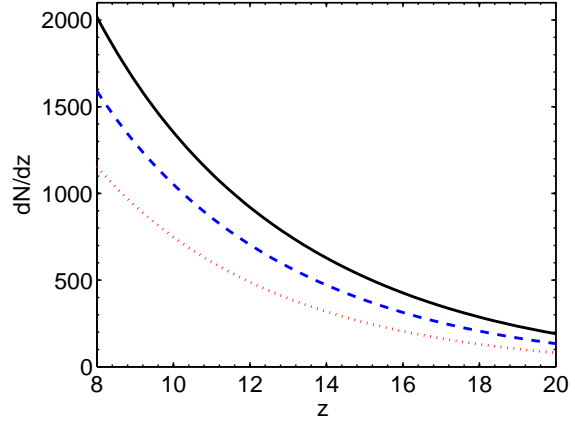


Figure 13. Theoretical evolution of line number density produced by minihalos/dwarf galaxies along a line of sight. The maximum halo mass is $10^{10} M_\odot$, and the minimum halo masses are $10^6 M_\odot$ (solid), $2 \times 10^6 M_\odot$ (dashed) and $5 \times 10^6 M_\odot$ (dotted), respectively.

since our model applies only to the early stages of reionization, when the stellar sources have not set up an ionizing background.

This line number density is also the probability $P(z)$ that a line of sight intersects an object in a redshift interval dz centered on z . In analogy to the method used in Furlanetto & Loeb (2002), we divide the observed frequency band into small bins, each of which corresponds to a redshift interval Δz that is small enough to make sure that the probability to have an intersection in each bin $P(z) \Delta z < 0.01$. Then we generate a random number R_i (uniformly distributed in $[0, 1)$) for each bin, and an intersection is said to take place if the condition $R_i < P(z) \Delta z$ is satisfied.

When an intersection occurs, we randomly choose a mass M for the intersected halo according to the mass function. With the halo mass and the redshift of that bin, we compute its formation redshift distribution, and z_F is Monte-Carlo sampled from the distribution curve. Then we use the star formation criterion described in section 2.2 to determine whether it is a minihalo in collisional ionization equilibrium or a dwarf galaxy photonized after a star

burst. For every dwarf galaxy, its metallicity is fitted as a function of halo mass to the results given by Salvadori & Ferrara (2009). As the fitted metallicity is always $\gtrsim 10^{-4}$, the IMF model-A is used. With the impact parameter randomly selected with an equal probability per unit area for each object, we compute the 21 cm line profile for every minihalo and dwarf galaxy intersected by a sightline. From 129 MHz ($z \sim 10$) to 158 MHz ($z \sim 8$), we found 3241 lines if we set $M_{\min} = 10^6 M_{\odot}$, out of which 210 lines are attributed to dwarf galaxies. That is about 6.5% of the lines coming from dwarf galaxies, and the rest come from minihalos. The relative transmission $T = \exp(-\tau)$ for a range of observed frequency corresponding to $z \sim 10$ is shown in Fig.14. The six panels from top to bottom show the results for $f_X = 0, 0.05, 0.1, 0.2, 1$ and 5 , respectively. $M_{\min} = 10^6 M_{\odot}$ is used for $f_X \leq 0.2$, $M_{\min} = 2 \times 10^6 M_{\odot}$ is used for $f_X = 1$, and we use $M_{\min} = 5 \times 10^6 M_{\odot}$ for the case of $f_X = 5$. Note that the y-axes are different between panels.

As seen from the figure, the absorption lines are very narrow and closely spaced, resembling a 21 cm forest. The depth of the 21 cm absorption strongly depends on the existence and the intensity of the uncertain X-ray background. The absorption strength is significantly increased if there is no X-ray background, and it decreases rapidly with the increase of the X-ray background, which ionizes and heats the gas in the IGM reducing the optical depth of both non-linear structures and the global absorption. Especially, if the X-ray background in the early universe was very strong (e.g. $f_X = 5$), resulted from a large number of high mass X-ray binaries in the case of top-heavy IMF towards high- z or from mini-quasars, we could hardly see any feature on a spectrum. This is because, on one hand, the line number density is reduced, and on the other hand, the absorption by non-linear structures is so weak that most lines are covered by the global absorption. For some minihalos, the gas outside r_{vir} contributes to the absorption far from the line center because of the infall velocity, and a few absorption lines of the neighboring halos overlap with each other on the wings. In this case the actual optical depth of each point is the sum over all the absorptions caused by these overlapping lines.

We compared two spectra: one taking into account the local X-rays contributing to heating and cascading to Ly α photons, the second neglecting the above. It turns out that for the IMF model-A and the relatively high metallicities that are used in the spectrum, the small amount of soft X-rays produced by the dwarf galaxies make little difference (less than 0.1%) even without an X-ray background. So we could not see any signature that can be attributed to them in the spectrum. However, if a dwarf galaxy with relatively high mass and (almost) primordial composition does exist, a top-heavy IMF (like the IMF model-C) is expected (Schneider et al. 2002, 2003), and the associated large HII region will result in a broad bump on the spectrum, erasing several absorption lines produced by neighboring minihalos.

Directly from the spectrum, we could compute the distribution of equivalent width of the absorption lines for a specific range of observed frequency corresponding to a specific redshift. As the continuum of a background source has a global decrement due to the absorption of the diffuse IGM, the real signal of non-linear structures is the extra absorption with respect to the flux transmitted through the IGM. Therefore, the equivalent width of an absorption line should be defined as

$$\begin{aligned} W_{\nu} &= \int \frac{f_c e^{-\tau_{\text{IGM}}(z)} - f_c e^{-\tau(\nu)}}{f_c e^{-\tau_{\text{IGM}}(z)}} d\nu \\ &= \int (1 - e^{\tau_{\text{IGM}}(z) - \tau(\nu)}) d\nu, \end{aligned} \quad (32)$$

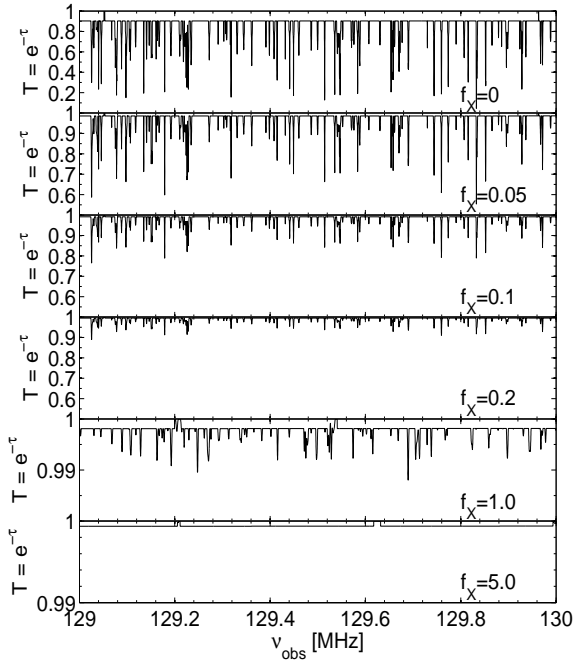


Figure 14. Relative transmission along a line of sight at redshift $z \sim 10$. The six panels from top to bottom show the results for $f_X = 0, f_X = 0.05, f_X = 0.1, f_X = 0.2, f_X = 1.0$, and $f_X = 5.0$, respectively. Note that the y-axes are different between panels.

where f_c is the continuum flux of the background radio source, and $\tau_{\text{IGM}}(z)$ is the optical depth of the diffuse IGM at redshift z . Using the theoretical spectrum of 129 – 133 MHz (corresponds to $z = 10.01 - 9.68$), we compute the cumulative distribution of equivalent width of those 21 cm lines around $z \sim 10$, which is shown in Fig.15. The dot-dashed, short dashed, solid, dotted, and long dashed curves take $f_X = 0, 0.05, 0.1, 0.2$, and 1 , respectively. As for the case of $f_X = 5$, the number of lines emerged from the IGM absorption in this frequency range is too small to derive any statistical implication, so the distribution of equivalent width is not shown for this case. For the fiducial value $f_X = 0.1$, the majority of absorption lines have equivalent widths around 0.03 to 0.3 kHz. We see that the number of large signals is very sensitive to the presence and intensity of the X-ray background. If there is no X-ray background ($f_X = 0$), then about 95% of absorption lines have $W_{\nu} > 0.1$ kHz. For the value $f_X = 0.05$, there are about 75% of lines with $W_{\nu} > 0.1$ kHz, while for $f_X = 0.1$ and 0.2 , this fraction drops to 45% and 15% respectively. If $f_X = 1$ or even higher, there will be no absorption line gets $W_{\nu} > 0.1$ kHz.

5 THE OBSERVABILITY

There are two kinds of radio sources which are potentially usable for absorption line studies at high redshifts during the epoch of reionization. One is the high redshift quasars, which are quite luminous, but so far no quasar has been confirmed at $z > 6.5$. The other candidate is the radio afterglows of GRBs. Although they are fainter than quasars, they are more likely to exist at higher redshifts. Also, they have simpler power-law spectra at low frequencies due to synchrotron self-absorption, so it may be easier to extract absorption signals from bright GRB afterglows. Here we examine the

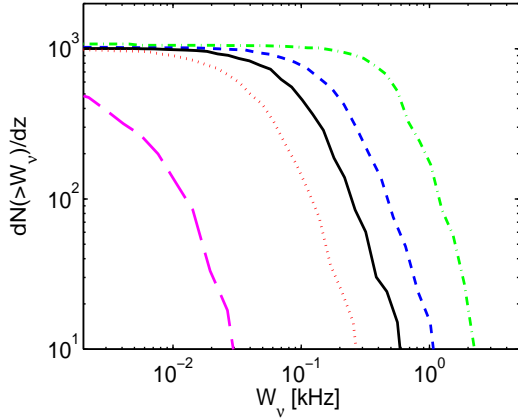


Figure 15. Cumulative distribution of equivalent width of the 21 cm absorption lines around $z \sim 10$. The dot-dashed, short dashed, solid, dotted, and long dashed curves are computed assuming $f_X = 0$, $f_X = 0.05$, $f_X = 0.1$, $f_X = 0.2$, and $f_X = 1.0$, respectively.

observability of 21 cm signals on both spectra of these background sources.

As for the upcoming and planned low frequency interferometers, a spectral resolution of 1 kHz is achievable for LOFAR³ and SKA⁴. From the theoretical spectrum computed above, we get about one absorption line in every 8.4 kHz at $z \sim 10$ on average when we use $M_{\min} = 10^6 M_{\odot}$ (line overlapping is accounted), and the line density (per observed frequency interval) is lower for lower redshifts or higher M_{\min} . On the other hand, the line width ranges mostly from ~ 1 kHz to ~ 5 kHz for halos of different masses. So the instruments can marginally resolve these 21 cm lines. While resolving the detailed line profile is probably out of reach, the line counting is feasible as long as sufficiently bright radio sources can be found at high redshift.

To produce mock spectra matching real observations, we degenerate the theoretical spectrum to a resolution of 1 kHz, add Gaussian noise onto each pixel with the signal-to-noise ratio $S/N = 5$, and convolve it with a continuum of GRB afterglow as well as a radio spectrum of quasar. Two synthetic spectra are illustrated in Fig.16 with the left panel for a GRB afterglow and the right panel for a quasar. We take $f_X = 0.1$ for both cases. The flux density of GRB afterglow is scaled to $100 \mu\text{Jy}$ at 200 MHz and $z = 6$, which is achievable for the afterglow of an energetic GRB produced by explosion of a massive metal-free star at high redshift, with isotropic energy of 10^{54} erg (Ioka & Mészáros 2005), and the spectral index is taken to be 2 ($F_{\nu} \propto \nu^2$), which is appropriate for the synchrotron self-absorption spectrum at the frequencies of interest (Frail 2003). The quasar flux density is scaled to 20 mJy at 120 MHz and $z = 10$, with a spectral index of -1.05 as fitted to the radio spectrum of the powerful radio galaxy Cygnus A (Carilli et al. 2002).

Apart from spectral resolution considerations, we also need high enough sensitivity to observe the absorption lines. In other words, with the planned instruments, the background source has to be bright enough to get the decrement of flux density higher than the detection limit. The minimum detectable flux density of an interferometer is related to the system temperature T_{sys} , the effective

aperture area A_{eff} , channel width $\Delta\nu_{\text{ch}}$, integration time t_{int} , and the signal-to-noise ratio S/N by

$$\Delta F_{\min} = \frac{2 k_B T_{\text{sys}}}{A_{\text{eff}} \sqrt{\Delta\nu_{\text{ch}} t_{\text{int}}}} \frac{S}{N}. \quad (33)$$

The real signals of minihalos or dwarf galaxies are their additional absorptions with respect to the absorption by the IGM, i.e. $\Delta F = F_{\nu} \exp(-\tau_{\text{IGM}}) - F_{\nu} \exp(-\tau)$. Equating this flux decrement to the detection limit, we get the minimum flux density of the background source required to observe the absorption lines:

$$F_{\min} = 542 \mu\text{Jy} \left(\frac{S/N}{5} \right) \left(\frac{0.1}{e^{-\tau_{\text{IGM}}} - e^{-\tau}} \right) \left(\frac{1 \text{ kHz}}{\Delta\nu_{\text{ch}}} \right)^{1/2} \times \left(\frac{5000 \text{ m}^2 \text{K}^{-1}}{A_{\text{eff}}/T_{\text{sys}}} \right) \left(\frac{30 \text{ days}}{t_{\text{int}}} \right)^{1/2}, \quad (34)$$

where the ratio $A_{\text{eff}}/T_{\text{sys}}$ is an intrinsic parameter describing the sensitivity of an interferometry array, and we use the value for SKA here. For the GRB afterglow, the integration time is limited by its fading time scale. Typically, after a bright, short-lived radio “flare” at early times, the subsequent evolution of the radio afterglow can be described by a slow rise to maximum, followed by several segments of power-law decays with a timescale of ~ 100 days (Frail 2003). Here we have assumed a reasonable integration time of 30 days, and find that a minimum flux density of $\sim 500 \mu\text{Jy}$ is required to detect the absorption lines with the resolution of 1 kHz for the case of $f_X = 0.1$.

As seen from the continua (dashed lines) in Fig.16, the flux density of our prototype GRB afterglow is more than one order of magnitude lower than this limit. Note that this is already an energetic GRB which is one order of magnitude brighter than normal GRBs. It may be possible that there are even brighter GRBs, but for most GRBs it seems that the radio afterglows would be too dim for being used as background source in observations with such a high spectral resolution. If we by chance find a quasar at very high redshift during the early stages of reionization, the signals could be easily detected. Especially, if one stacks together several lines to get an average profile, it will hopefully reveal the horn-like profiles we found.

Alternatively, we may try broadband observations with lower resolution. In this case, we could use the standard measurement of D_A , i.e. the mean (relative) flux decrement in each band, in analogy to the Ly α forest experiments of quasars (Rauch 1998). We redefine the mean flux decrement with respect to the continuum after the absorption by the IGM:

$$D_A = \left\langle \frac{f_{\text{IGM}} - f_{\text{obs}}}{f_{\text{IGM}}} \right\rangle = \langle 1 - e^{-\tau_{\text{IGM}} - \tau} \rangle = 1 - e^{-\tau_{\text{IGM}} - \tau_{\text{eff}}}, \quad (35)$$

where the angular brackets represent the average over each band and τ_{eff} is the effective optical depth of the band. D_A measures the excessive absorption by minihalos/dwarf galaxies compared to the diffuse IGM, and the different values of D_A measured in different bands represent the absorptions at different redshifts, showing the evolution of non-linear structures during the epoch of reionization. In terms of D_A , the flux decrement can be written as $\Delta F = F_{\nu} \exp(-\tau_{\text{IGM}}) - F_{\nu} \exp(-\tau_{\text{eff}}) = F_{\nu} D_A \exp(-\tau_{\text{IGM}})$, then the requirement of the background source is

$$F_{\min} = 77.4 \mu\text{Jy} \left(\frac{S/N}{5} \right) \left(\frac{0.99}{e^{-\tau_{\text{IGM}}}} \right) \left(\frac{0.01}{D_A} \right) \times \left(\frac{5 \text{ MHz}}{\Delta\nu_{\text{ch}}} \right)^{1/2} \left(\frac{5000 \text{ m}^2 \text{K}^{-1}}{A_{\text{eff}}/T_{\text{sys}}} \right) \left(\frac{30 \text{ days}}{t_{\text{int}}} \right)^{1/2} \quad (36)$$

³ <http://www.lofar.org/index.htm>

⁴ <http://www.skatelescope.org/>

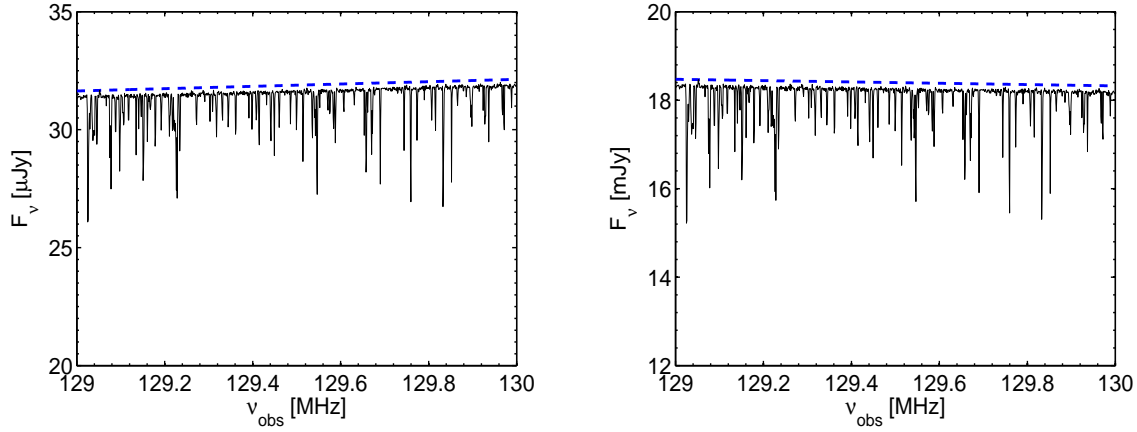


Figure 16. Synthetic spectra of 21 cm absorptions against a GRB afterglow (left panel) and a quasar (right panel) with 1 kHz resolution. The corresponding redshift is $z \sim 10$, and the unabsorbed continua are shown as the dashed (blue) lines. $f_X = 0.1$ is assumed for both spectra.

With the broadband observation, the major concern is that the available length of the line of sight is limited. On one hand, we wish to put the background source as far as possible in order to get enough bands to see varying D_A values at different redshifts. On the other hand, as the source moves farther, it gets dimmer, lower the average signal to noise ratio, then an even broader band is required to detect the signal, thus beyond a certain distance the number of useful bands might decrease again. An optimal source redshift z_{GRB} can be found to maximize the number of available bands. Considering the applicability of our model, we set the lower limit of the redshift to be $z_{\text{lim}} = 8$, and find that the optimal redshift for the GRB is $z_{\text{GRB}} \sim 9.8$. This redshift depends mainly on the lower limit of the redshift we set, but of course it is also dependent somewhat on the reionization history, e.g. D_A which evolves slowly with redshift. This does not depend on the observational parameters. The optimal redshift is quite encouraging given that we have already seen 2 GRBs beyond $z = 6$.

The existence of an X-ray background and its intensity are crucial in determining the observability of the signals. If there is no X-ray background, then with a GRB at redshift 9.8 and with the pixel resolution of $\Delta\nu_{\text{ch}} = 1.38$ MHz, we can get 19 bands, then 19 values of D_A . We plot the D_A as a function of observed frequency in the upper panel of Fig.17, and with the Gaussian noises of $S/N = 5$, the expected spectrum after the absorption by minihalos and dwarf galaxies F_ν is shown in the bottom panel of Fig.17. The original continuum F_c and the flux density absorbed by the homogeneous IGM F_{IGM} are also shown for comparison. With SKA, we could hopefully detect the non-zero D_A s if $f_X = 0$ or it is extremely small, which are signals from both minihalos and dwarf galaxies. In addition, D_A decreases statistically with the decreasing redshift, which is a clear signature of the evolution of non-linear structures during the epoch of reionization. In the case of $f_X = 0.05$, we could marginally observe 2 pixels on a spectrum from 131.5 MHz to 158 MHz, one of which has a band width of ~ 8 MHz (131.5 – 139.5 MHz) with the mean flux decrement of $D_A \approx 0.017$, and the other has a band width of ~ 18.5 MHz (139.5 – 158 MHz) with the mean flux decrement of $D_A \approx 0.009$. However, if f_X takes our fiducial value 0.1, then even one band spanning the whole spectrum from the source to the lower redshift limit is still not broad enough to make the observation feasible. The situation gets worse for higher values of f_X . Thus, the 21 cm broadband observation against high redshift GRBs can be a power-

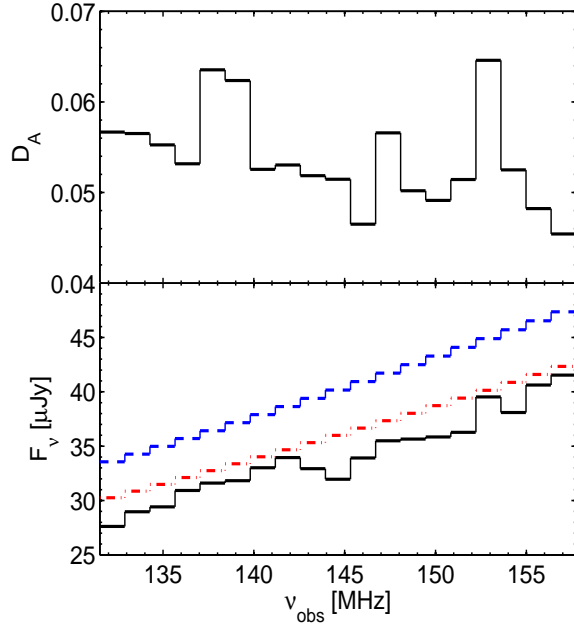


Figure 17. The mean flux decrement with respect to the continuum absorbed by the diffuse IGM (*upper panel*) and the synthetic broad band spectrum with 1.38 MHz resolution (*bottom panel*) in the case of $f_X = 0$. The 19 pixels show the frequency range corresponding to the redshift range from 9.8 to 8. In the *bottom panel*, the dashed, dot-dashed, and solid lines are the original continuum flux density, the flux density absorbed by the homogeneous IGM, and the expected flux density after the absorption by minihalos and dwarf galaxies, respectively.

ful probe of the presence and the intensity of the early X-ray background and the thermal evolution during the epoch of reionization.

6 DISCUSSION

We have modeled in detail the gas density and velocity profiles, ionization state, temperature profiles, and Ly α photon production for both minihalos and dwarf galaxies during the early stages of

reionization when the IGM was still patchy. We also take into account an early X-ray background, which could partially ionize and heat the IGM, and suppress the formation of low mass minihalos. Using the detailed model, we investigate the spin temperature of neutral hydrogen at different radii and the optical depth profiles of 21 cm absorption lines, for various impact parameters, halo masses, and redshifts.

We find that the $\text{Ly}\alpha$ background and the $\text{Ly}\alpha$ photons from recombinations in the slightly ionized IGM couple the spin temperature to the kinetic temperature outside minihalos or HII regions of dwarf galaxies, and the coupling is already strong at redshift 10. The $\text{Ly}\alpha$ background photons are blocked at surfaces of halos, and the $\text{Ly}\alpha$ photons from recombinations are negligible inside low-mass halos, though it dominates over the collisional coupling in high-mass halos in which the gas is partially ionized by collisions. The collisions also couple the spin temperature to the gas kinetic temperature effectively at the center, but this coupling decreases and the spin temperature decreases with increasing radius.

The infalling velocity of gas around the minihalos/dwarf galaxies plays a very important role in determining the profiles of the 21 cm lines, double-peaked horn-like profiles are produced for a vast range of parameters. The line profile of a dwarf galaxy also depends on the size of its HII region, and hence its radiative properties. The horn-like profile disappears for galaxies which are large, or with top-heavy IMF so that the HII region expands beyond the turning point of gas velocity. The optical depth of a dwarf galaxy is lower for lines of sight penetrating through its HII region, while a sufficiently large HII region will lead to an optical depth trough rather than an absorption line.

With the line number density based on halo mass function and a physically motivated criterion for star formation, we generate synthetic spectra of 21 cm forest by Monte Carlo procedure, and calculate the cumulative distribution of equivalent width of the absorption lines. Most of these lines have equivalent widths around $0.03 \sim 0.3$ kHz for an X-ray background intensity parameter of $f_X = 0.1$, and the number of strong signals with large equivalent widths decreases significantly with increasing f_X . We then study the observability of these signals. For high resolution (1 KHz) observations, the GRB radio afterglows are too dim to be used as the background, but absorption lines should be easily detected for a high redshift quasar. It is exciting to know that the Pan-STARRS⁵ (the Panoramic Survey Telescope And Rapid Response System) is being developed which will be able to detect quasars up to redshift ~ 7 and aims to find $\sim 20 - 50$ quasars at $z \sim 7$. For broadband observations, it is also possible to detect the absorptions against GRB radio afterglows if there is no X-ray background. Setting a lower redshift cut-off at $z_{\text{lim}} = 8$, we find that the optimal redshift for the GRB is $z_{\text{GRB}} \sim 9.8$. With a sensitivity of SKA, a signal-to-noise ratio of 5, and a reasonable integration time, we could get measurements of mean flux decrement D_A for 19 bands along the line of sight, each with a channel width of 1.38 MHz. In this way we could detect not only the signals from both minihalos and dwarf galaxies, but also their evolution during the epoch of reionization. However, the detectability of 21 cm signals is very sensitive to the presence of an early X-ray background. If an early X-ray background existed but was not strong, taking $f_X = 0.05$, we could marginally observe 2 pixels along the line of sight towards a GRB which is located at the optimal redshift of 9.8. Nonetheless, for the value of $f_X = 0.1$ or higher, the signal will be impossible to be de-

tected. Therefore, the 21 cm absorption could be a powerful probe of the presence/intensity of the X-ray background and the thermal history in the early universe. However, we note that it is difficult to find a radio source before the IGM has been significantly ionized or heated, especially for a very bright high redshift quasar.

Furlanetto & Loeb (2002) studied the 21 cm forest signals of minihalos and early galaxies. Here, we have re-investigated this problem with different and more detailed modeling of various properties of these nonlinear objects, an early X-ray background, as well as the $\text{Ly}\alpha$ background during the epoch of reionization. We found stronger absorption signals from both minihalos and dwarf galaxies for an early X-ray background not higher than the level today. Given the many different model parameters adopted, this is not unexpected. There are many differences in the details of modeling between the two papers, but the main difference seems to be the IGM temperature. Furlanetto & Loeb (2002) have assumed a heated IGM with a simple form of its evolution with redshift, which is already heated up to 1000 K at $z = 10$. This lies between our cases of $f_X = 1$ and $f_X = 5$. But in our fiducial model, the gas temperature in the IGM is about 35 K at the same redshift for $f_X = 0.1$. This is appropriate for the early stages of stellar reionization, when the percolation has not occurred yet. In Furlanetto & Loeb (2002), the gas structure in the infalling region around minihalos/dwarf galaxies is modeled with a self-similar solution of secondary infall found by Bertschinger (1985), while we have used the gas infall model developed by Barkana (2004) which is based on the extended Press-Schechter model and spherical collapse. The Bertschinger's solution has a power law density profile of $\rho \propto r^{-2.25}$, which is much steeper than the Barkana's prediction. Our density and peculiar velocity structure of the infalling gas, with the lower spin temperature outside the minihalos/HII regions, produce a higher optical depth and a horn-like profile, which was not found in Furlanetto & Loeb (2002). For the dwarf galaxies, Furlanetto & Loeb (2002) considered protogalactic disks, whereas we assume here a spherical symmetry in the gas density distribution since the earliest galaxies are not likely to have large angular momentum.

In addition to the early X-ray background, an obvious uncertainty in our model is the production of soft X-rays by dwarf galaxies in the early universe. Especially with the normal IMF model-A and relatively high metallicity, the amount of soft X-rays emitted after a star burst is very uncertain (Schaerer 2003). However, this amount of soft X-rays produced by stellar sources is always negligible as compared to the background X-rays even if $f_X = 0.05$. Another uncertainty comes from the gas density in minihalos and dwarf galaxies. We have neglected the possible change of density profile after the star formation. The gas density profile could be modified by the expansion of the HII region when the ionizing front changes nature from R-type to D-type. There are also uncertainties in the star formation history in the dwarf galaxy. We have assumed that the feedback effects quench subsequent star formation (c.f. Omukai & Nishi 1999), so that a single star burst is produced. We have also assumed a smooth gas density distribution, neglecting cool dense gas clumps from which the first stars are likely to form. Thus we may have overestimated R_{HII} , and the optical depth could be slightly higher if they are accounted for. However, the gas fraction in minihalos or dwarf galaxies could also be lower than the cosmic mean value (Naoz et al. 2009), then the optical depth will be lower. Also, the results depend on the assumption of f_{esc} , which is taken to be 0.07, in agreement with current observations.

As illustrated in Fig.9 and Fig.11, minihalos and dwarf galaxies exhibit distinct optical depth profiles mainly due to the different

⁵ <http://pan-starrs.ifa.hawaii.edu/public/home.html>

ionization state and coupling physics, so they are potentially distinguishable. Although we may not be able to resolve the line profiles with the upcoming and planned instruments, it is encouraging to be able to distinguish their features in a statistical way, given that dwarf galaxies span a different halo population from mini-halos which cannot host stars. We reserve this investigation to future works.

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